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The 21 August 1986 Lake Nyos
Gas Disaster, Cameroon

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EXECUTIVE SUMMARY

The sudden catastrophic release of gas from Lake Nyos on 21 August 1986 caused the deaths of at least 1700 people in the northwest area of Cameroon. An eleven-person multidisciplinary team was sent for three weeks to investigate the cause and to recommend steps to mitigate future hazards of this nature. The results of the field and laboratory investigations are:

- * Lake Nyos occupies a volcanic crater that was formed by a violent explosion only a few hundred years ago. Underlying the lake is a volcanic pipe that serves as a conduit for the gradual upward migration of carbon dioxide (CO₂) from deep within the earth. Over a long period of time, gas dissolved in groundwater has been accumulating in the bottom water of the lake, creating a potential hazard.
- * Chemical, isotope, and geologic evidence supports the hypothesis that the CO₂ was derived from deep-seated magmatic sources, but that no direct volcanic activity was involved in the disaster.
- * An undetermined mechanism triggered a catastrophic release of CO₂ from the lake, which created a lethal cloud that flowed downhill into populated areas.
- * The victims exposed to the cloud rapidly lost consciousness due to displacement of oxygen in the air and high levels of CO₂. Death was due to asphyxiation. Skin lesions on many survivors are thought to be pressure sores due to long periods of unconsciousness and immobility.
- * High concentrations of CO₂ remain dissolved in Lake Nyos, representing a potential hazard until they can be safely lowered. The possibility of a failure of the weak natural dam at the lake outlet poses an additional hazard.
- * Other lakes in northwest Cameroon may also have the potential for catastrophic release of lethal quantities of CO₂. Field investigations are required to identify those lakes.
- * A method is proposed to reduce or eliminate the gas hazard at Lake Nyos and at other potentially dangerous lakes that may be revealed by future field investigations.

INTRODUCTION

Cameroon is a country of about 8.5 million people located on the west coast of Africa (fig. 1). English and French are the official languages. In the northwest part of the country, there is a volcanic zone characterized by many craters filled with beautiful lakes. Lake Nyos is one such lake: located high in the mountains, normally deep blue in color, peaceful.

On Thursday evening, 21 August 1986, tragic events occurred at this idyllic lake that made it known throughout the world as a "killer lake." The early part of the evening began with heavy rains and thunderstorms typical of the rainy season. By 9:30 P.M., however, the weather was calm, the air temperature cool, and most people were engaged in their usual evening activities. This tranquil scene was suddenly disturbed by a series of rumbling sounds lasting perhaps 15-20 seconds. Many people in the immediate area of the lake came out of their homes, experienced a warm sensation, smelled rotten eggs or gunpowder, and rapidly lost consciousness. Other individuals either became unconscious without preliminary symptoms, or never awakened from their sleep. One observer, who was on high ground above Lake Nyos, reported hearing a bubbling sound. Walking to a better vantage point, he saw a white cloud rise from the lake, accompanied by a large water wave that washed up onto the southern shore. None of the survivors in the valley saw a visible cloud.

Survivors of the incident awakened 6 to 36 hours later, and many found that their oil lamps had gone out while still containing oil, their animals and members of their family were dead, and they themselves were weak and confused. About 1,700 people and 3,000 cattle died near the lake and along drainages up to 10 km north of the lake. The pattern of death within this region was definitely not uniform. For example, in the Nyos area there was a pen with four of the five goats dead, and nearby a home where only four of the nine family members survived. Cattle in the lower lying areas perished, while those at the higher

elevations were still grazing normally. Many small animals died, but many others were still alive. The bird and insect populations were significantly reduced for at least 48 hours, but the plant life remained essentially unaffected. As best as could be determined, however, the humans and animals that did not survive died very quickly with no signs of panic or discomfort.

On Friday morning, 22 August, people from the surrounding villages began to drift into the area and start the grim task of recovery and burial. It was not until Saturday morning that the rest of the world heard of the incident, after two helicopter pilots from Helimission (a Swiss missionary service) flew into the area and quickly reported their findings. The pilots and other people approaching the lake on Saturday or Sunday reported no general discomfort or problems related to breathing.

As best as could be ascertained, there were no premonitory changes in Lake Nyos that served to forewarn of the incident. Following the event, however, the water level was noted to have dropped about one meter, and there was vegetation damage showing that a large water surge had washed up the southern lake shore to a height of about 25 m. A water surge 6 m in height had overflowed the spillway (frontispiece, lower right), and a fountain of water or froth had splashed over an 80 m high rock promontory on the southwestern side of the lake. On Saturday morning, a transient white chalky substance was noted covering the rocky cliffs on the west side of the lake, but this was not present when we arrived. We did find that the water was calm, but had turned a rusty-red color with mats of vegetation floating on the surface. The household goods in the homes surrounding the lake were undisturbed, and rocks perched precariously on the cliffs at the edge of the lake had not been shifted. There was, however, one small area on the steep west side of the lake which showed evidence of a fresh landslide, that could have occurred either just before, during, or after the incident.

A similar catastrophic event occurred at Lake Monoun, about 95 km to the southeast in August 1984. In the Monoun disaster,

37 people died after walking into a visible cloud around the lake. An evaluation, done seven months after the incident, concluded that the causative agent was carbon dioxide (CO₂) released from the lake (Sigurdsson and others, in press). According to local legends, there may have been at least three additional incidents where exploding lakes or mass deaths have occurred in this same area of Cameroon (E. Shanklin, per. comm., 1986).

Because of the previous incident at Lake Monoun, and the many unanswered associated questions, a more extensive and timely evaluation of the Lake Nyos event was immediately initiated, and a diversified, ten-member scientific team consisting of forensic pathologists, geologists, water chemists, environmental engineers, a limnologist, and a clinical physician was organized and sent on short notice to Cameroon. The team arrived in Yaounde on Wednesday, 27 August 1986. The following report is a summation of its 3-week field evaluation of the area plus the results of later analytical studies.

GEOLOGY

Regional

A number of small, young basaltic volcanoes have formed cinder cones and lava flows in northwest Cameroon along part of the "Cameroon Volcanic Line", a northeast-southwest (NE-SW) trending zone of crustal weakness that extends 1,600 km from islands in the Atlantic ocean into northwestern Cameroon and northeastern Nigeria (Fitton, 1980). Volcanic explosions have also formed numerous circular craters (maars), many of which are now occupied by deep crater lakes. The reconnaissance geology of this area is described by Peronne (1969).

The Lake Nyos Area

Lake Nyos, 310 km northwest of Yaounde, is a classic maar, formed in a coarse-grained biotite-quartz monzonite (granitic)

terrain of uncertain, pre-Tertiary age (older than 65 million years). This rock is overlain by a deeply weathered, red-orange soil. The granitic terrain is cut by prominent faults which are marked by pronounced erosional lineaments, including the linear Nyos valley north of Lake Nyos. Many volcanoes are localized along these faults.

Lake Nyos is one of three eruptive features in the immediate area. The others are prominent basaltic cinder cones located 1 km to the NE and 2 km to the south (fig. 2). Although the Lake Nyos crater may be the oldest of these eruptive features, it is still very young. Judging by the unweathered and little-eroded ash deposits on its flanks, it may be only a few hundred years old. The lake is 1,925 m in maximum length (elongated NW-SE), and 1,180 m in maximum width. It is shallow at the southern end, but drops off steeply to a large, flat plain at a depth of 208 m (fig. 3). This plain is formed of silt and mud of unknown thickness. Electron microprobe analysis of one sediment sample from the bottom indicated the presence of feldspar, quartz, biotite, and kaolinite; no fresh volcanic constituents were observed.

About two-thirds of the Lake Nyos crater is rimmed by quartz monzonite, and the rest by ash beds that were mainly erupted at the time of crater formation. These ash beds consist principally of pyroclastic surge deposits (deposits formed by violent explosions that accompanied crater formation). The irregularly bedded deposits are up to 30 m thick at the crater rim, but thin very rapidly and become finer-grained away from the crater. Maximum size of rock fragments (clasts) increases upwards in the deposit, suggesting increased violence later in the crater-forming event. Ultramafic fragments (fragments rich in Fe and Mg) are common in the upper third of the surge deposits, and are up to 25 cm in size. These fragments, carried to the surface from great depths, are composed mostly of the minerals olivine, orthopyroxene, clinopyroxene, and spinel. They contain abundant tiny fluid inclusions of CO_2 and H_2O . Many of the ultramafic

clasts are mantled by olivine-plagioclase basalt (a dark, silica-poor volcanic rock), and angular basalt clasts are common throughout the surge deposits. The ash beds are moderately well consolidated near the crater rim, but are poorly consolidated and easily erodable on the flanks. They form vertical cliffs along the NE rim, and are sufficiently durable to form the resistant bed of the stream draining Lake Nyos to the NW. This stream plunges over a 35- to 40-m-high waterfall after descending a few meters below lake level, leaving a 40-m wide septum or "spillway" to bound Lake Nyos on the north (frontispiece). The thickness of ash underlying the spillway is not known. The pyroclastic surge deposits were originally deposited around the entire circumference of the lake, but they are now exposed discontinuously around the southern end of the lake. This suggests that they may have been eroded away by waves generated by previous gas events.

Origin and Subsurface Structure of Lake Nyos

The formation of the present Lake Nyos crater was preceded by a short period of relatively quiescent eruptive activity, as indicated by fire-fountain volcanic deposits and a thin basalt flow exposed beneath pyroclastic ash beds on the northeast shore of the lake. The volume of the ejected pyroclastic material is considerably less than the volume of the present maar crater, indicating that the Lake Nyos crater was formed in part by collapse of adjoining rocks.

The Lake Nyos maar is undoubtedly underlain by a diatreme (a near-vertical pipe-like conduit consisting largely of fragmental, permeable ash; see Hearn, 1968; Lorenz, 1986). A schematic cross-section of this diatreme (fig. 4) shows a complex pipe filled with fragmented rocks and ash, and intruded by volcanic material. The diatreme was formed above a dike (lava-filled crack) of ascending, volatile (gas)-rich basaltic magma (molten rock), whose source lay within the Earth's mantle (fig. 5) as evidenced by the abundant ultramafic fragments. This rising

basaltic magma explosively fragmented as it neared the Earth's surface, either by release of dissolved magmatic volatiles or by contact with meteoric (near-surface) water. The diatreme could extend to as much as 2-3 km depth (Lorenz, 1986), to a point where it becomes transitional to its feeder dike.

GAS ORIGIN

There are three potential sources for the gas released on 21 August: *volcanic*, *magmatic*, and *biogenic*. Our distinctions between the terms *volcanic* and *magmatic* as used in this report are important. As used here, *volcanic* gas is associated with high-temperature, near-surface eruptive processes; *magmatic* gas is released from magma deep within the earth, is relatively cool by the time it reaches the surface, and has lost its reactive constituents such as sulfur and chlorine compounds and carbon monoxide. *Biogenic* gas is produced by decomposition of organic matter and has a low temperature.

Based on geophysical and geochemical evidence, it has been inferred that the mantle source region of basaltic Cameroon magmas lies at depths greater than about 90 km (e.g., Gumper and Pomeroy, 1970; Fitton and Dunlop, 1985). In addition, the isotopic and trace-element geochemistry of Cameroon magmas suggest that they are derived from parent melts produced by very small degrees of partial melting of the mantle (e.g., Fitton and Dunlop, 1985). These two critical observations help explain why Cameroon magmas tend to be rich in CO₂.

Specifically, the deep source region exists at pressures so great that any carbon at those depths is likely to exist as the carbonate mineral dolomite rather than in a fluid phase (Wyllie, 1979). Under these conditions, small degrees of partial melting of the mantle result in rapid breakdown of the carbonate mineral, which then enters the melt, making the melt very CO₂-rich. If such melts begin to ascend from the source region toward the lower pressure surface, they cannot retain high concentrations of CO₂ in solution, and will begin to degas some of their dissolved CO₂ at depths between 80 and 100 km (Wyllie, 1979).

Furthermore, crystallization of any magma that proceeds to advanced degrees within the crust will lead to saturation of H_2O or CO_2 in the residual melt, and a gas phase may begin to separate from the melt, creating bubbles. The bubbles have a strong tendency to ascend buoyantly, first through the melt and then up along grain boundaries in overlying crustal rocks. If such gases reach the surface by rising along crustal faults, they may simply escape to the atmosphere and safely dissipate. If, however, such gases are prevented from reaching the atmosphere, they may begin to accumulate. In Cameroon, potential accumulation sites include possible near-surface voids within the disrupted feeder conduits of old volcanic craters, ground water, or stratified crater lakes. Therefore, it is not necessary to invoke special geologic conditions in order to explain the accumulation of CO_2 -rich gas in Lake Nyos and environs.

Distinctions between High- and Low-Temperature Gas

Temperature profiles of Lake Nyos taken on 4 and 5 September indicate that the water was relatively cool and nearly isothermal after the event (fig. 6). The bottom temperatures in Lake Nyos were no higher than those in other tropical lakes at similar elevation and latitude (fig. 7). We could not substantiate a report by a few local villagers of hot water in the Lake Nyos outflow stream near Nyos village.

A volcanic injection of magma or gas into the lake would have been accompanied by an input of heat and an increase in water temperature. For example, during volcanic injection of lava and gas into the Soufriere crater lake (St. Vincent) water temperatures reached $82^{\circ}C$ (Sigurdsson, 1977). On the basis of maximum cooling rates in tropical lakes (Wood and others, 1976), Lake Nyos could have dissipated only enough heat in the 12 days prior to our sampling to decrease the temperature at each depth by $0.5^{\circ}C$. Thus, the supposition of a significant heat input becomes untenable.

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We sampled water from the maar Lakes Nyos, Barombi Mbo, Bambuluwe, Nyi, and Wum; one cold freshwater spring above Lake Nyos; local precipitation; and two soda springs approximately 40 km south of Lake Nyos.

Only the top 10 m of Lake Nyos contained measurable dissolved oxygen (table 1). Precipitation of ferric hydroxide in the oxygenated surface waters was responsible for the lake's reddish-brown color; below 10 m the water was clear.

The chemistry of Lake Nyos surface water before the event is presented in table 2 (Kling, 1985). The composition of the bottom water before the event is unknown. The most noticeable change in surface-water chemistry after the event was an increase in the concentration of most elements (tables 2 and 3). The concentrations of many solutes (dissolved substances) showed a definite increase with depth, implying either that the bottom water was more concentrated than the surface water prior to the event, or less likely, that there had been incomplete mixing of a recent input of solutes near the bottom.

Any large input of lava or volcanic gas into the lake would add sulfur and chlorine compounds. Again, an example of this is found in Soufriere crater lake, where large increases in concentrations of sulfur and chlorine compounds accompanied volcanic injection (Sigurdsson, 1977). Lake Nyos, however, shows no such enrichment of sulfur and chlorine compounds in either lake waters or sediments. Hydrogen fluoride is also a common volcanic gas (table 4), but its aqueous form was nearly absent from Lake Nyos.

Based on our field sampling, we estimate that one liter of hypolimnetic water in Lake Nyos contains one to five liters of dissolved gas. Carbon dioxide comprises 98 - 99 percent of the dissolved gas. The non-volcanic character of the gas is most apparent in the low concentrations of carbon monoxide, hydrogen, hydrogen sulfide, and sulfur dioxide compared to those in volcanic gas (table 4). Studies of volcanic emanations from magmas similar in composition to those erupted in Cameroon,

notably those from Iceland and Hawaii, show that the relative proportions of CO₂ and sulfur in near-surface volcanic gases vary within certain limits. The weight ratio of CO₂ to sulfur in such volcanic gases is typically less than 100 (Gerlach, 1986; Arnorsson, 1986). In contrast, the ratio CO₂ to sulfur for Lake Nyos bottom waters is greater than 10⁴. The water temperature, composition of dissolved gases, and the low sulfur content of Lake Nyos waters and sediments does not support a hypothesis of recent, direct injection of lava or volcanic gas.

Distinctions between Low-Temperature Gases:

Magmatic versus Biogenic

This distinction is best made by examination of carbon-14 isotopes, which undergo constant decay, and thus can be used as a dating tool. Biogenic carbon, the carbon incorporated in organisms living in lakes, is enriched in recently produced carbon-14 and, therefore, has a young age. Carbon in magmatic gas has an infinitely old apparent age. A preliminary carbon-14 date of >35,000 BP (years before present) obtained from CO₂ gas dissolved in Lake Nyos strongly suggests that the carbon dioxide is mainly magmatic rather than biogenic. One could argue that this carbon-14 date is reflecting old organic carbon in the sediments or water. This argument, however, is not supportable since Lake Nyos is probably no more than a few hundred years old.

A ratio of helium-3 to helium-4 isotopes greater than 1 demonstrates the presence of significant amounts of magmatic gas (Hooker and others, 1985; these ratios are relative to the atmospheric standard). The ratio of 6 in Lake Nyos clearly supports the conclusion that the gas is magmatic rather than biogenic. Our minimum estimate of helium-3 concentration in the lake of $2.9 \times 10^{-7} \text{ } \mu\text{mol L}^{-1}$ is very much greater than any possible enrichment from tritium decay, which also produces helium-3.

The stable carbon isotope composition ($\delta^{13}\text{C}$) of CO₂ and methane in lakes may also distinguish between biogenic and magmatic sources. The average values of $\delta^{13}\text{C}$ in the CO₂ and

bicarbonate dissolved in Lake Nyos and the two soda springs we sampled range from -0.7 to -8.0 per mil (parts per thousand; table 5). These values are consistent with the hypothesis of a magmatic carbon source, but they cannot be used to definitely rule out a biogenic gas source because they fall in the range where biogenic and magmatic carbon values overlap.

There does appear to be some biogenic gas in Lake Nyos, although it is limited to very small amounts as evidenced by the carbon-14 data. The $\delta^{13}\text{C}$ value of the methane (composing <0.3 percent of the dissolved gas), for instance, indicates production by a biogenic pathway (for comparison, see Whiticar and others, 1986; Deuser and others, 1973). Taken together, however, the carbon-14, He, and $\delta^{13}\text{C}$ data clearly indicate that almost all of the carbon dioxide in Lake Nyos is of magmatic origin.

Gas Accumulation

Numerous springs in Cameroon contain high concentrations of dissolved CO_2 (Marechal, 1976). We feel that the high concentrations in these springs could not be produced by biogenic processes. The relative proportions of ions found in one nearby soda spring are similar to the major-ion chemistry of Lake Nyos (fig. 8). Both the spring and Lake Nyos waters are significantly enriched in magnesium relative to the other lakes and springs in the area. This similarity suggests a common origin for the spring and lake water. This common ground-water source contains large amounts of CO_2 and could have provided a means by which dissolved CO_2 entered the lake and was stored in the bottom waters.

In order for the dissolved CO_2 to build up to high concentrations in the lake, the bottom waters cannot be brought to the surface where they would lose CO_2 to the atmosphere. Relatively little mixing of surface and bottom waters occurs in lakes that are stratified. This condition is produced by a layer of less dense water overlying a layer of more dense water (fig. 9). Stratification resulting from a large density difference may

persist for long periods of time, allowing buildup of solutes and dissolved gases in the bottom waters. The observed vertical distribution of solutes in Lake Nyos suggests that the lake was stratified before the event. In addition, movement of dissolved iron from deep waters to the surface, where the iron combined with oxygen to form a reddish precipitate, indicates that some mixing of surface and bottom waters occurred during the event.

Oxygen and hydrogen isotopes are useful in studying the history and origin of waters. In order to test the hypothesis that CO_2 entered the lake dissolved in ground water, we examined the isotopic composition of the lake waters. The isotope data of all the lakes and springs are plotted in figure 10. These data are similar to the trends produced by evaporative concentration or by mixing of groundwater and surface water. If evaporative concentration is the only process affecting the waters studied, both $\delta^{18}\text{O}$ and δD values should increase with increasing ionic strength. Our data show an inverse relationship, however, with Lake Monoun and Lake Nyos being intermediate between the springs and the waters of the remaining lakes (figs. 11a and 11b). The isotope data and the vertical distribution of solutes are therefore consistent with the hypothesis that the CO_2 in Lake Nyos entered as dissolved in ground water and accumulated in the bottom waters.

RELEASE OF GAS FROM THE LAKE

The hypothesis of gas storage in the bottom waters requires that the amount of CO_2 released could have been dissolved in the lake. Our calculations show that Lake Nyos could hold 1.5 km^3 of CO_2 at full saturation. Preliminary reports indicate that the bottom waters of Lake Nyos are still 30 percent saturated with CO_2 (S. Aramaki, per conversation, 1986). Assuming pre-event saturation, the lake could have released about 1.0 km^3 of CO_2 . Release of 1.0 km^3 would have caused lake level to drop approximately 90 cm, which is in accord with the observations of Helimission pilots and local villagers.

The gas cloud was produced by the rapid exsolution of large amounts of CO_2 from the lake. This gas rose, expanded, and pushed up overlying water. The effervescing gas made a considerable rumbling noise as it escaped from the lake, and then rose until its momentum was overcome by gravity. The burst of gas leaving the lake resulted in the formation of surface waves.

The distribution of dead cattle around the lake indicates that the gas cloud initially rose approximately 100 m above the crater rim. Because CO_2 is denser than ambient air the cloud tended to maintain its integrity (pure CO_2 is 1.54 times more dense than atmospheric air under similar conditions). As it emerged from the lake, the gas cloud filled the lake basin by displacing the ambient air, and then spilled over the crater rim into low-lying areas. Flow of CO_2 at lethal concentrations into topographic lows has been well documented in previous studies (e.g., LeGuern, and others, 1982).

A characteristic, thick "head" would have formed along the front of the advancing cloud as it started to move down-gradient (fig. 12). The head of the flowing cloud probably maintained the highest concentrations of CO_2 , because it would have been continually recharged from the faster flowing tail (Simpson, 1982). This means that the head of the cloud would have remained lethal to greater distances than one might expect.

Because of imprecise time observations, it was not possible to determine how fast the head of the cloud advanced down the river valleys. We can infer, however, that there would be a tendency for the flow to become stretched out and slowed down due to friction on the cloud from trees and other obstacles in the flow path. This would result in dispersion and partial dissipation of gas behind the flow front, and would create areas of significant concentrations of CO_2 in topographic depressions, in areas of dense vegetation, and in enclosed spaces. These gas pockets could linger for long periods of time.

Analysis of the location of reported deaths has shown that the total surface area affected was about 29 km^2 . When

estimating the volume of CO₂ released from Lake Nyos, assumptions were made regarding the height of the gas cloud in given areas. These assumptions included an initial cloud height of 100 m; between Lake Nyos and the village of Nyos, the cloud height was assumed to have tapered from 100 to 50 m. The minimum volume estimate of a 100 percent CO₂ cloud that would fill the described area and account for all fatalities is 0.9 km³, a value just less than our estimate of the maximum volume released during the event. This estimate is conservative because concentrations of CO₂ above 10 percent are lethal to humans.

Given that, before the event, the gas was probably dissolved in the bottom waters, we now examine the possible mechanisms for release. These mechanisms include an internal wave, a seismic shock, a landslide into the lake, or any disturbance of this metastable system. During our study in late August, we observed that water brought to the surface from a depth of 5 m effervesced. This suggests that nucleation sites in these lakes are not a limiting factor, and that bubble formation is spontaneous upon pressure reduction under supersaturated conditions. As a parcel of water is moved toward the surface, the total pressure decreases until saturation conditions are met and bubbles form. The distance moved is the critical amplitude of vertical water movement required to initiate degassing.

The Lake Nyos event could have been triggered by any disturbance that moved water vertically a distance greater than the critical amplitude. Internal wave movements that occur at the boundary between two layers of water at different densities are common in lakes. They are most often generated and intensified by wind stress or traveling pressure fields (fig. 13). It is not yet possible to estimate a likely internal wave amplitude in Lake Nyos because the fundamental fluid dynamics equations do not apply in a system where expanding gas is producing turbulence. However, measuring the actual amplitude of internal water movements and comparing them to the critical amplitude as calculated from the CO₂ saturation would provide a means of monitoring the stability of the lake.

Significant seismic activity during or preceding the event was not observed at the Kumba recording station 220 km southwest of Lake Nyos. Several large boulders still perched on topographic high points around the lake, and the neatly stacked household goods in many homes imply that the magnitude of any local shock was negligible. Anecdotal evidence from survivors also does not support the hypothesis of a seismic shock. There was a fresh landslide scar on the western cliffs of the lake, although we found no evidence of anomalies in sediment topography in the western basin.

If a reservoir of gas were contained below the lake sediments, then a sudden release of the gas would likely disrupt the bottom topography during its ascent through the sediments. A series of four depth-sounding profiles across the lake revealed no crater or disturbance on the lake bottom corresponding to a localized vent. Any release of gas through the sediments also would have dispersed particles of fine sediment up into the water. No suspended sediment particles were detected in any water sample taken below 5 m. Settling times of fine sediment would be very slow (see Chow, 1964), and outflow rates are too small in Lake Nyos to account for removal of deep suspended sediment by flushing. The lack of evidence for bottom disruption and suspended sediment argues against the possibility that the gas released was stored beneath the lake.

PATHOLOGY

Based on survivor reports and initial surveys, definite similarities exist between the 1986 Lake Nyos disaster and the Lake Monoun disaster of August 1984. No autopsies were performed on victims of the Lake Monoun disaster. In the Lake Nyos incident, although somewhere between 1500 and 2000 persons died, all bodies were rapidly buried. One victim, who survived for several days, was preserved for examination at the hospital in Wum. For these reasons, we were faced with a considerable problem in gathering medical information. The medical team's

investigations at Lake Nyos were subsequently directed into four areas: (1) the interviewing, examination and photography of survivors hospitalized at Nkambe and Wum; (2) postmortem examination of human and animal fatalities; (3) site investigations at the Subum, Nyos, and Fulani villages, as well as at Lake Nyos itself, with an emphasis on biological observations; and (4) analysis of photographs and movies taken by Helimission missionary pilots who were some of the first outsiders in the area on 23 August 1986.

Survivors from Nyos, Subum, Cha, Fang, and Fungam were interviewed at the government hospitals in Wum and Nkambe. Based on their testimonies, there appeared to be a changing spectrum of perceptions and symptoms as a function of distance from the lake. Survivors from Nyos and surrounding Fulani settlements, localities within 3 km of the lake, described two different experiences. Fifty percent (20 of 40) of those interviewed described no unusual odor or taste. They did described fatigue, light headedness, warmth, and confusion prior to collapsing and being unconscious for up to 36 hours. Upon awakening, they did not complain of eye irritation or pain, and at the hospital they did not exhibit any skin lesions. Their admitting hospital diagnoses related primarily to trauma from falls and included temporary paralysis and loss of feeling attributed to fractures, dislocations, or prolonged lying in fixed positions.

The other 50 percent of the Nyos area victims described an odor of rotten eggs, burning eyes, and difficulty in breathing, followed by collapse and varying periods of unconsciousness. These people showed local skin lesions, predominantly unilateral and overlying bony prominences, and occasionally showed skin lesions on the torso and legs. The skin lesions displayed sharply circumscribed borders and showed a central area of injured tissue. There was no reddening of the margins suggesting that the overall appearance was that of traumatic pressure sores rather than chemical burns. Frequently, these lesions were covered by an eschar, or crust. This group of survivors also

complained of nausea, vomiting, and diarrhea, all of which are consistent with symptoms of carbon dioxide poisoning (von Oettingen, 1958).

In contrast to the complaints of patients from the Nyos area, all survivors from Subum (approximately 10 km from Lake Nyos) described the odor of rotten eggs or gunpowder, associated with difficulty in breathing, hyperventilation, fatigue, confusion, and profound weakness prior to collapse. Periods of unconsciousness ranged from several hours to as long as 36 hours. All hospitalized survivors had discrete skin lesions limited to one side of the face or arms. Several had burns involving up to 15 to 25 percent of the body surface area. These people uniformly experienced nausea, vomiting, and diarrhea upon awakening, and many complained of burning eyes. The ocular complaints resolved within several days without specific treatment. Except for a 25-year-old female with pneumonia who had been successfully treated with intravenous antibiotics, no survivors had significant pulmonary complaints lasting more than 36 hours. All women and new-born infants confined in the second floor of the Subum maternity dispensary, which was the only two story structure in Subum, survived and showed minimal physical findings. Other people in the rest of Subum either died or were significantly affected.

Missionary pilots from Helimission who arrived Saturday morning, 23 August, described a spectrum of survivors and fatalities, including people, mammals, birds, amphibians, and reptiles. Most deaths appeared to the missionaries to have occurred quickly because there was little evidence of agonal struggle (such as furniture or personal belongings in disarray). Additionally, many victims were found in their beds still covered by bed clothing. Victims found outside appeared to have collapsed suddenly without substantial movement. Animals were described as "dead in their tracks" in herds rather than dispersed. The Helimission pilots described skin blisters and blood-tinged fluid flowing from the mouths and nostrils of the

deceased as well as a bloated appearance of the faces. These observations were confirmed in the photographs taken at the time by the pilots, and are felt to be typical of early postmortem decomposition. The Helimission pilots also noted blistered lesions on the faces of some survivors which presumably were the same skin lesions observed in hospitalized patients on 29 and 30 August.

An autopsy was performed on a 30-year-old male from Nyos who died 2 days after admission to the hospital at Wum. The body had been embalmed as a means of preservation. The cause of death was pneumonia involving both lungs. There were no skin lesions. Another male victim was examined on site following exhumation at Subum. Postmortem decomposition was moderately advanced, but tissue specimens were obtained for analysis. Pulmonary congestion and edema were not evident. Additional material collected by Cameroonian physicians from a male victim on 27 August 1986 in Subum was also analyzed. Tissues obtained at autopsies conducted in the field showed decomposition, but no specific pathology. Toxicologic analyses on the specimens from the three autopsied human victims were negative for cyanide, carbon monoxide, and sulfur compounds. Small quantities of alcohol found in human material and not in animal material supports premortem alcohol consumption versus decomposition change.

It is the opinion of the forensic pathology evaluation team that the human and animal victims died of asphyxia secondary to exposure to the CO₂ gas cloud. The best medical and scientific evidence at this time indicates that carbon dioxide was the toxic agent. Asphyxia is, by definition, the deprivation of the body or its vital parts (viz., the brain) of oxygen. In this incident, asphyxia resulted from the displacement of the normal atmosphere (approximately 21 percent oxygen) by a cloud of carbon dioxide gas. Under such circumstances victims will literally "drop in their tracks" after taking a few breaths and experience no feeling of suffocation. The actual mechanism of death is

believed to be a paralysis of the respiratory centers in the brain by the very high concentrations of carbon dioxide. Lethal levels of carbon dioxide are in the range of 8 to 10 percent (Sittig, 1985). There is no toxicologic evidence implicating hydrogen cyanide, carbon monoxide, or hydrogen sulfide in the deaths. The description of the odor of "rotten eggs" or "gunpowder" by many survivors, although usually associated with sulfur gases, is also commonly described by individuals exposed to high concentrations of carbon dioxide (White and others, 1952). This phenomenon is termed an "olfactory hallucination". In addition to the sense of smell being impaired by high levels of carbon dioxide, other senses may be affected as well. The feeling of warmth may be a sensory hallucination because 60 percent of known cases exposed to an atmosphere containing 6 percent CO₂ experienced sweating (White and others, 1952). Additionally, fatigue, headaches, and nausea were relatively common in this group.

Reports of the 1984 Lake Monoun event describe fatalities with skin lesions, distended abdomens, and puffy faces as well as mucus and blood flowing from the nose and mouth (Sigurdsson and others, in press). Our analysis of photographs of similar findings in victims of the 1986 Lake Nyos event leads us to believe that the lesions described at Lake Monoun were merely those of postmortem decomposition. Survivors of the Lake Monoun event also described feelings of nausea, dizziness, and generalized weakness when they approached the gas cloud, which was suspended 0-3 meters above the ground. One survivor from the Lake Monoun incident spent a week in the hospital being treated for gastrointestinal complaints. He had no skin lesions or difficulty in breathing, but he complained of body aches and joint pains. He described the smell of the gas as "sulfurous, like car battery liquid", as did other survivors.

We divide the skin lesions seen in the survivors of the Lake Nyos incident into three groups. The first and largest group of survivors had skin lesions which they attributed to exposure to

the gas, but we recognized clinically as being other disease processes which clearly antedated 21 August 1986.

The second group of survivors had bed-sore-like areas usually on one side of the face overlying bony prominences. Such lesions were healing and were virtually identical to traumatic skin lesions previously described in survivors of drug-induced comas. In the drug patients where these lesions were felt to result from localized pressure associated with prolonged lying in fixed positions while in a comatose state (Mandy and Ackerman, 1970). Because many of the patients at Nyos gave a history of being comatose for up to 36 hours, and also complained of temporary paralysis caused by lying in fixed positions for long periods of time, the explanation of skin lesions caused by pressure is quite plausible.

The third group of survivors consisted of five to ten victims who exhibited thermal burns that may represent injuries that were incurred while the victims were lying in a comatose state near heat sources. For example, one elderly lady had collapsed with her right hand and forearm coming to rest in a cooking fire. Notably, there was no reflexive withdrawal from the painful stimulus. Upon awakening, her hand and forearm were so severely burned that amputation was required. Several elderly people and two children had extensive second degree burns on their chests and abdomens; these burns may also have resulted from prolonged exposure to heat sources.

We could find no references in the medical literature relating specific skin lesions to carbon dioxide exposure, and we therefore conclude that none of the skin lesions resulted directly from this type of gas exposure. We also do not feel that the skin lesions resulted from exposure to a blast of hot gas, because none of the victims exhibited singeing of the hair, flash burns, or damaged clothing.

Vegetation samples from the Lake Nyos' area were examined for physical damage and chemically analyzed for traces of volcanic gas (H. Heggestad; M. Millard; W. Wergin; per. comm., 1986).

None of the plants surrounding the lake showed visible signs of chemical burns or heat stress by either infrared photography or gross examination. Much of the grass near the northern and southern shores was flattened or uprooted by the passing water waves. Slight damage to lower leaf surfaces was evident in three samples when compared to controls collected from distant locations. Results from x-ray photoelectron spectroscopy, scanning electron microscopy, and energy dispersive x-ray analyses showed no significant differences in structural features or elemental composition between the Lake Nyos samples and the controls. Because stomates are closed at night in most plants, the uptake of any poisonous gas into the plant would be reduced. Some plant species may be more susceptible than others, and so we cannot exclude short term plant injury due to airborne gases.

CONCLUSIONS

Lake Nyos is a classic maar, formed in a coarse-grained biotite-quartz monzonite of uncertain, pre-Tertiary age. On the basis of the geochemical and geophysical characteristics of Cameroon magmas, it is not necessary to invoke special geologic conditions in order to explain the accumulation of CO₂-rich gas in Lake Nyos and environs.

The temperature, composition of dissolved gases, and the low sulfur content of lake waters and sediments do not support a hypothesis of recent, direct injection of lava or volcanic gas. Taken together, the carbon-14, helium, and ¹³C (CO₂) data clearly indicate that almost all of the carbon dioxide in Lake Nyos is of deep-seated magmatic origin.

The similarity in relative proportions of solutes in Lake Nyos and a nearby soda spring suggests a common origin for the spring and lake water. This common source contains large amounts of CO₂; hydrogen and oxygen isotope data are consistent with the hypothesis that CO₂ entered the lake dissolved in groundwater. The lack of evidence for bottom disruption and suspended sediment

argues against the possibility that the gas was stored in fissures beneath the lake and then explosively released. Lake stratification prior to the event is indicated by the present vertical distribution of solutes. If persistent, this stratification would allow CO₂ to accumulate in bottom waters. If saturated before the event, Lake Nyos could have released about 1 km³ of CO₂, an amount slightly greater than the minimum volume estimate of a 100 percent CO₂ cloud that would fill the affected area and account for all fatalities. The trigger that released gas from the lake is unknown, although, if waters were supersaturated before the event, any small disturbance of the water column would initiate degassing.

Interviews with survivors and pathologic studies indicated that victims rapidly lost consciousness and that death was caused by asphyxiation. Carbon dioxide will produce these effects. At nonlethal levels, CO₂ acts like an anesthetic and can produce hallucinations, such that many people exposed to CO₂ will report the odor of sulfur compounds when none are present. Skin lesions found on survivors represent pressure sores, and in a few cases, exposure to a heat source such as cooking fires. There is no evidence of flash burns from exposure to hot gases. Finally, all other findings on the deceased can be explained by postmortem decomposition.

REMAINING HAZARDS

Associated with Lake Nyos

The tragic gas release of 21 August was probably not the first such event at Lake Nyos, judging from geologic evidence (see Geology section), although such occurrences are uncommon. A large amount of CO₂ remains dissolved in the lake, and until it is removed, the lake cannot be regarded as being completely safe.

Another hazard associated with Lake Nyos involves the stability of the spillway which drains the lake to the north

(frontispiece; fig. 2). The spillway is formed by relatively weak pyroclastic ash beds. If these ash beds were to fail, a catastrophic flood would move down stream valleys, destroying Nyos village, Subum, and other populated areas to the north. A rapid lowering of the Lake Nyos surface level could also cause depressurization of the water column, triggering another gas release event.

Other Areas of Northwest Cameroon

The deep maar lakes of northwest Cameroon must all be regarded as potentially capable of lethal gas release until proven safe. Much preliminary work to evaluate this hazard has already been done by George Kling.

The northwest Cameroon maar lakes all appear to be geologically young (of Quaternary age; some have doubtless formed within the past few hundred years). The formation of new maars in the future is quite likely and will be accompanied by catastrophic ash deposition that could be lethal to residents over areas as much as 10 km in diameter.

RECOMMENDATIONS

Required Field Investigations

We have concluded that slow "leakage" of carbon dioxide gas from magmatic sources beneath the Earth's surface was involved in setting the stage for the Lake Nyos tragedy. The rate at which the gas is being supplied to the lake system will be critical to determine the potential for, and timing of, future gas releases. This will require repeated sampling of the deep lake water in the future to determine if dangerous levels of dissolved CO₂ have built up within the lake. Saturation levels of gas can be calculated after collecting the water with a standard water sampler that has been modified to allow expanding gas to fill an attached bell jar instead of leaking out into the water as the sample is brought to the surface.

Nine of the approximately 40 crater lakes in Cameroon have not yet been sampled to determine if their bottom waters contain anomalously high levels of dissolved carbon dioxide. As dangerous lakes are identified, a profile of common characteristics (age, geographic position, geological and limnological features, etc.) should be compiled. This would facilitate identification of dangerous lakes in Cameroon, as well as suggesting potentially hazardous lakes in other countries.

Sediment cores should be collected from Lake Nyos and other lakes to evaluate the historical record of lake mixing and prior gas release events.

Anthropologists should conduct interviews with people living adjacent to northwest Cameroonian lakes to identify and evaluate any legends pertaining to the origin of the lakes or to accounts of mass deaths in this area.

The narrow spillway draining Lake Nyos should be studied in detail to evaluate its structure, stability, and potential for collapse.

Direct Risk Mitigation

The gas content of lakes found to contain dangerously high levels of dissolved CO_2 should be lowered. This could be accomplished by "controlled degassing", as described in Appendix II. Lake Nyos is an obvious candidate for development of this technology. If judged to be unsafe, the spillway draining Lake Nyos should be removed to eliminate the potential for catastrophic failure. This could be accomplished either by explosive demolition after lowering of the lake to safe levels, or by gradual "staged" excavation. Thorough pre-removal engineering studies would be required in either case.

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Table 1. Dissolved oxygen in four lakes in the Lake Nyos areas, Cameroon.

Lake	Depth (m)	Oxygen (mg/L(O ₂))
Nyos	0	8.55
	2.6	2.67
	5.4	2.40
	10	<0.02
	>10	<0.02
Nyi	0	9.05
	10	9.15
	25	7.50
	45	0.50
Bambuluwe	0	9.30
	10	8.70
	20	0.50
	30	0.15
	45	<0.02
Barombi Mbo	0	9.80
	10	7.75
	20	6.80
	30	6.40
	45	1.00
	55	<0.02
	>55	<0.02

Major Element Chemistry (mg/L)													
Lake	Depth(m)	Date Collected	pH	HCO ₃	Cl	SO ₄	Al	Ca	Fe	K	Mg	Na	Si
Nyos	0 ¹	8 May 85	7.1	21	0.12	.08	0.3	2.3	<.01	1.2	1.5	2.2	5.5
	0	4 Sept 86	5.9	165	0.36	0.20	<0.1	14	1	3	16	6.4	10
	2.6	4 Sept 86	5.6	195	0.33	0.10	<0.1	16	8.1	3	19	7.2	12
	5.4	4 Sept 86	5.5	245	0.46	0.11	0.1	19	14	3	23	8.5	13
	10	3 Sept 86	5.1	265	0.49	0.14	0.1	20	17	3	24	8.6	13
	12	4 Sept 86	5.6	270	0.40	<0.1	<0.1	20	18	4	25	9.1	14
	52	2 Sept 86	5.2	400	0.68	0.12	0.5	26	25	5	32	12	17
	103	2 Sept 86	5.3	560	0.72	0.13	0.5	37	58	6	46	16	21
	103	4 Sept 86	5.4	535	0.55	0.11	0.2	35	56	6	43	15	21
	155	2 Sept 86	5.3	635	nd	nd	0.5	39	66	6	48	17	23
	200	3 Sept 86	5.5	455	0.56	0.14	0.2	31	40	5	38	13	18
	201	4 Sept 86	5.7	725	0.80	0.11	0.2	46	71	7	57	19	26
Wum	0	4 Sept 86	7.0	26	0.27	0.12	<0.1	2.9	0.13	1	2.5	1.2	3.5
Nyl	0	11 Sept 86	6.4	43	0.30	0.33	<0.1	4.9	0.05	2	3.6	3.5	5.0
	45	11 Sept 86	6.5	63	0.31	0.14	<0.1	7.0	1.5	3	4.2	4.1	6.9
Bambuluwe	0	10 Sept 86	6.7	9	0.41	0.31	0.2	.94	0.09	1	0.36	0.70	2.7
	45	14 Sept 86	6.2	33	0.37	0.20	<0.1	1.2	6.5	2	0.43	0.70	3.9
Barombi Mbo	0	14 Sept 86	7.5	29	0.78	0.25	0.2	2.8	0.07	1	2.5	2.4	6.0
	10	14 Sept 86	7.2	28	0.65	0.20	<0.1	2.8	0.02	1	2.5	2.4	5.7
	20	14 Sept 86	7.1	28	0.69	0.27	<0.1	2.9	0.02	1	2.5	2.4	5.8
	30	14 Sept 86	7.1	27	0.76	0.21	<0.1	2.5	0.07	<1	2.2	2.1	5.8
	45	14 Sept 86	7.0	30	0.72	0.15	<0.1	2.5	0.07	<1	1.9	1.9	6.0
	55	14 Sept 86	6.9	40	0.70	<0.1	<0.1	3.7	3.2	1	2.5	2.4	6.6
	90	14 Sept 86	6.6	45	0.71	0.10	0.2	3.7	0.98	1	2.7	2.5	7.9
Monoun ²	0	2 Mar 85	6.9	88	<1	<1	nd	8.7	0.01	2.2	6	9.4	8.9
	15	2 Mar 85	5.8	265	1.8	<1	nd	20	0.03	4.7	22	17	19
	61	2 Mar 85	6.3	1050	3.2	<1	nd	41	200	5.6	29	25	16
	90	2 Mar 85	6.4	1050	3.4	<1	nd	42	220	5.7	30	24	21
Nyos rain		1 Sept 86			0.14	0.59							

¹George Kling, unpublished data. Samples filtered through 1.2 µm glass fiber filter.²Sigurdsson and others, in press.

Table 3. Minor- and trace-element composition data for waters in lakes and springs in the Lake Nyos area, Cameroon. Sampling dates same as in Table 2. All cyanide concentrations <200 µg/L had all fluoride concentrations <10 µg/L)

Lake	Depth (m)	Minor and Trace Element Chemistry (µg/L)							
		Ba	Co	Li	Mn	Ni	Sr	V	Zn
Nyos	0	32	4	5	480	16	88	<6	50
	2.6	39	5	6	560	21	84	<6	135
	5.4	44	6	7	660	30	96	<6	54
	10	49	6	7	690	24	105	<6	70
	12	48	7	7	720	25	105	<6	60
	52	73	9	9	940	37	180	7	57
	103	118	13	11	1350	44	195	15	54
	103	108	13	11	1250	40	180	15	145
	155	132	17	11	1400	43	250	18	36
	200	96	11	9	1050	35	170	10	110
	201	137	16	13	1600	51	240	17	94
Wum	0	140	<3	<4	12	<5	42	<6	89
Nyl	0	6	<3	<4	9	<5	56	<6	<3
	45	17	<3	<4	820	<5	71	<6	9
Bambuluwe	0	5	<3	<4	6	<5	17	<6	9
	45	29	<3	<4	750	<5	13	<6	8
Barombi Mbo	0	15	<3	<4	7	<5	37	<6	<3
	10	14	<3	<4	3	<5	37	<6	<3
	20	15	<3	<4	5	<5	38	<6	4
	30	13	<3	<4	23	<5	33	<6	<3
	45	20	<3	<4	140	<5	32	<6	<3
	55	48	<3	<4	760	<5	48	<6	5
	90	50	<3	<4	870	<5	48	<6	5

Table 4. Gas concentrations in volume percent exclusive of water vapor in Lake Nyos and Soda Springs in the Lake Nyos area, Cameroon and user volcano, Japan. "nr" means not reported. Additional gas analyses by U.S. Environmental Protection Agency are shown in Appendix III.

	Lake Nyos 103 m (2 Sep 86)	Lake Nyos 155 m (2 Sep 86)	Lake Nyos 103 m (4 Sep 86)	Lake Nyos 200 m (3 Sep 86)	Soda spring (Luhi) (11 Sep 86)	Soda spring (Gasei) (11 Sep 86)	Usu Volcano ¹ (28 Sep 79)
He	0.0005	0.0005	0.0006	0.0005	0.0013	<0.0001	0.0003
H ₂	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0001	8.16
Ar ²	0.0110	0.0066	0.0150	0.0150	0.0150	0.200	0.0010
O ₂ ²	0.0918	0.0672	0.229	0.288	0.0512	2.65	nr
N ₂ ²	0.508	0.337	0.851	0.892	0.708	10.2	1.35
CH ₄	0.257	0.248	0.290	0.286	0.0029	0.110	<0.0001
CO ₂	98.9	99.0	98.4	98.3	98.9	86.6	64.9
HCN	<0.001	<0.001	<0.001	<0.001	<0.001	<0.002	nr
H ₂ S	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0005	15.6
CO	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0001	0.111
SO ₂	<0.005	<0.005	<0.005	<0.005	<0.005	<0.01	5.90
Hydrocarbons in ppm:							
C ₂ H ₆	0.1	0.1	0.1	<2	<2	0.1	nr
C ₂ H ₄	<2	0.1	<0.05	<2	<2	<0.05	nr
C ₃ H ₈	<2	<0.02	<0.01	<2	<2	0.06	nr
C ₃ H ₆	<2	0.03	0.01	<2	<2	0.02	nr
i-C ₄ H ₁₀	<2	<0.02	<0.01	<2	<2	<0.02	nr
n-C ₄ H ₁₀	<2	0.04	0.02	<2	<2	0.05	nr
Totals	99.8	99.7	99.8	99.8	99.7	99.8	100.0

¹ Calculated from Matsuo and others, (1982), who also report 2.97% HCl and 1.02% HF.

² Except for the Usu sample, some of the Ar, O₂, and N₂ is from atmospheric contamination during sample collection

Table 5. Isotopic composition data for waters and dissolved gas in lakes and springs, rocks and minerals from Nyos area, Cameroon. $\delta^{13}\text{C}$ HCO_3 values for water samples are for dissolved carbon fixed as SrCO_3 . $\delta^{13}\text{C}$ - CO_2 values are for CO_2 gas in the water.

Sample	Depth	$\delta^{18}\text{O}_{\text{SMOW}}$	$\delta\text{D}_{\text{SMOW}}$	$\delta^{13}\text{C}_{\text{PDB}}\text{-HCO}_3$	$\delta^{13}\text{C}_{\text{PDB}}\text{-CO}_2$
Nyos-	0 m	-2.1	-17		
	2.6 m		-14		
	5.4 m	-1.3	-13		
	10 m			-2.9	
	12 m	-1.5	-13		
	52 m	-1.7	-13	-4.5	
	103 m	-1.9	-14	-2.2	-3.4
	103 m	-1.8	-14		-3.2
	155 m	-1.9	-15	-2.0	-3.4
	200 m	-2.0	-16	-3.8	-3.3
	201 m	-2.0	-15	-3.4	
Wum-	0 m	+2.3	+4		
Nyi-	0 m	+0.4	-3		
	45 m	+0.1	-6		
Bambuluwe-	0 m	+0.7	-4		
	45 m	+0.7	-4	-7.2	
Barombi Mbo-	0 m	+1.0	-3		
	10 m	+0.7	-2		
	20 m	+0.7	-2		
	30 m	+0.8	-2		
	45 m	+0.6	-2		
	55 m	+0.1	-6		
	90 m ¹	+0.1	-6	-6.9	
Monoun-	0 m ¹	-2.5	-15	-3.2	
	15 m	-4.1	-22	-5.8	
	31 m	-4.3	-22,	-4.6	
	46 m	-4.5	-23	-4.3	
	61 m	-4.3	-24	-3.0	
	90 m	-4.5	-27	-3.2	
Nyos-rain		-4.7	-39		
Nyos-bucket		-3.7	-36		
Nyos-river		-2.5	-16		
Nyos Palace Spring		-2.7	-17		
Luih Soda Spring		-5.8	-28	-7.2	-8.0
Gesel Soda Spring		-7.6	-35	-0.7	-8.0
Kangwa Trona		+50.4		+2.0	
Nyos Gabbro w/calcite		+16.1		-4.9	
Pyroxene (silicate oxygen)		+5.2			

¹Sigurdsson and others, in press.

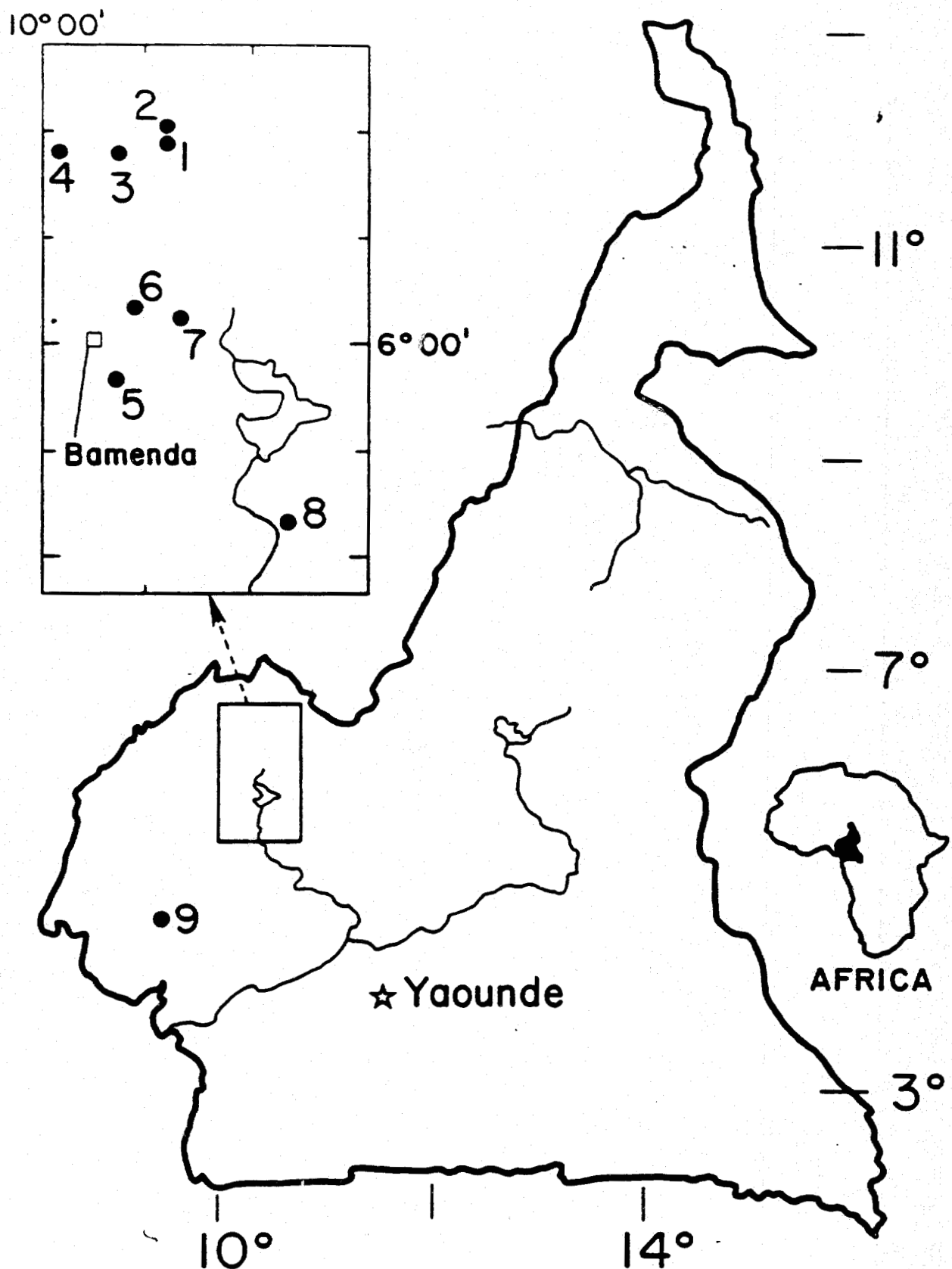
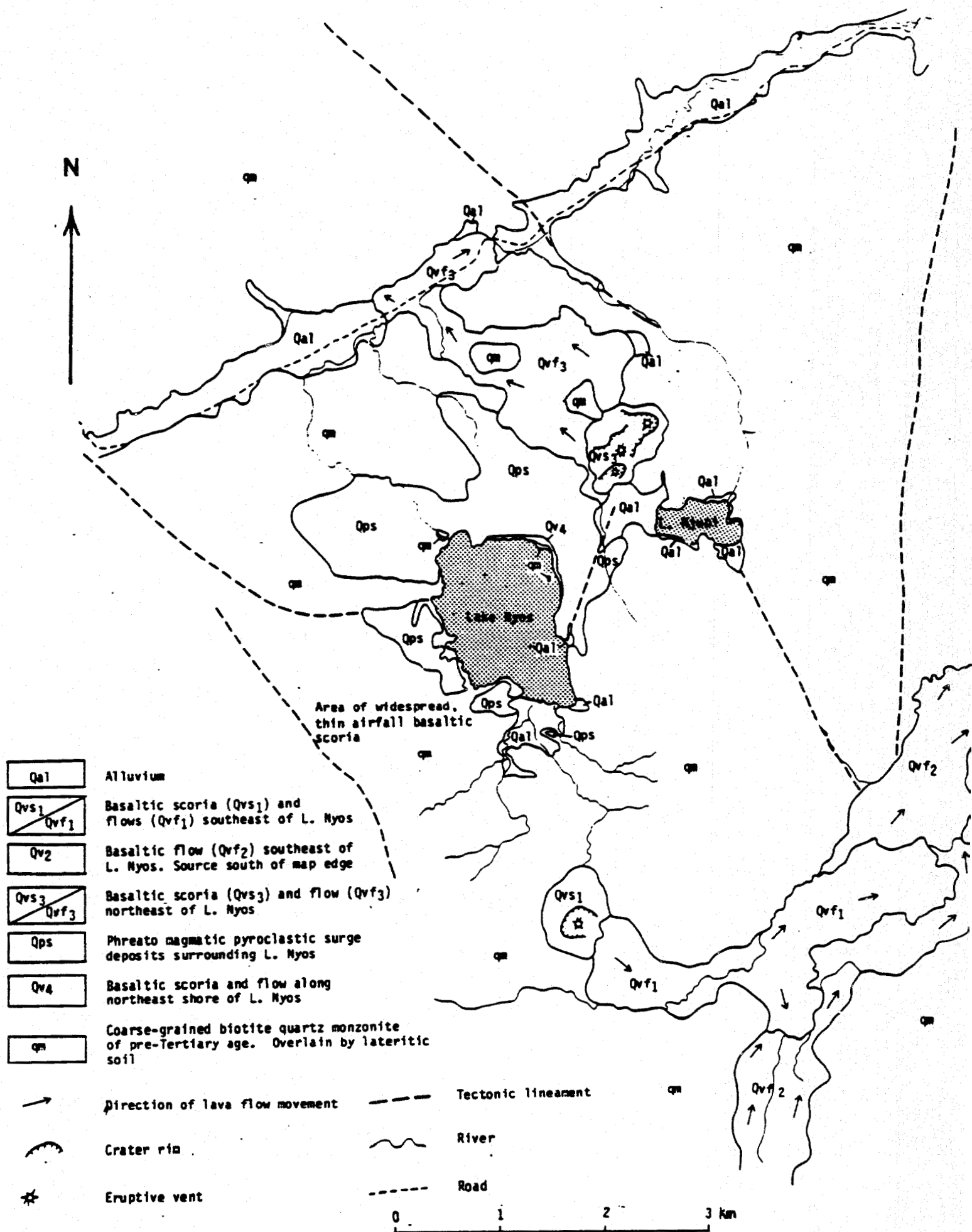
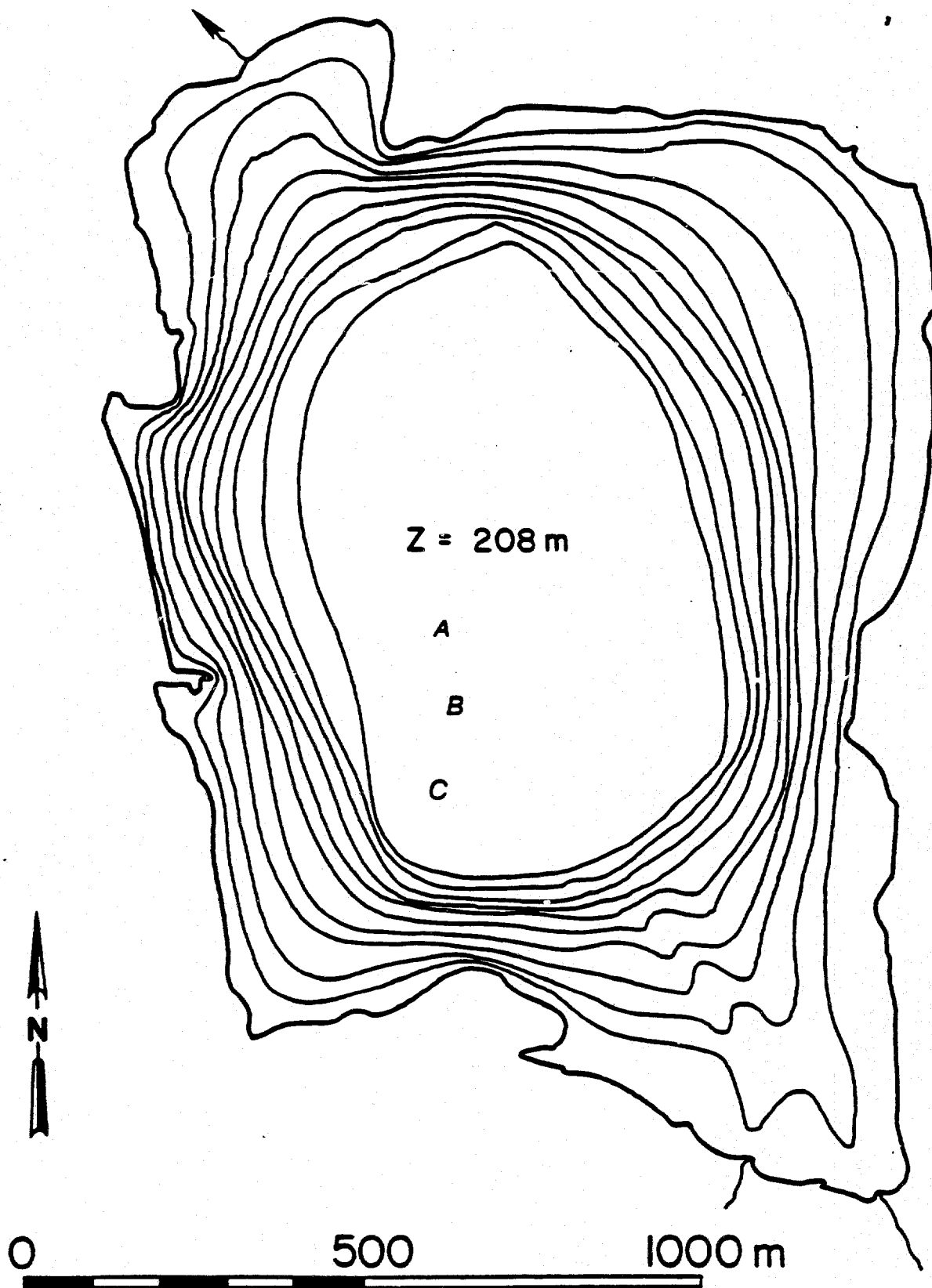


Figure 1. Location of Cameroon and northwestern lakes. Labeled sites: 1= Lake Nyos; 2 = Nyos spring; 3 = Lake Nyi; 4 = Lake Wum; 5 = Lake Bambuluwe; 6 = Luil spring; 7 = Gesel spring; 8 = Lake Monoun; 9 = Lake Barombi Mbo.

Figure 2. Photoreconnaissance geologic sketch map of the Lake Nyos area, Cameroon





CONTOUR INTERVAL = 20 m

Figure 3. Bathymetric map of Lake Nyos. Station A = samples collected on 2 September 1986; Station B = samples collected 3 September 1986; Station C = samples collected 4 September 1986. Lake volume = $1.765 \times 10^9 \text{ m}^3$; mean depth = 111.7 m maximum depth (Z) = 208 m; surface area = $1.58 \times 10^6 \text{ m}^2$. (Modified from Hassert, 1912.)

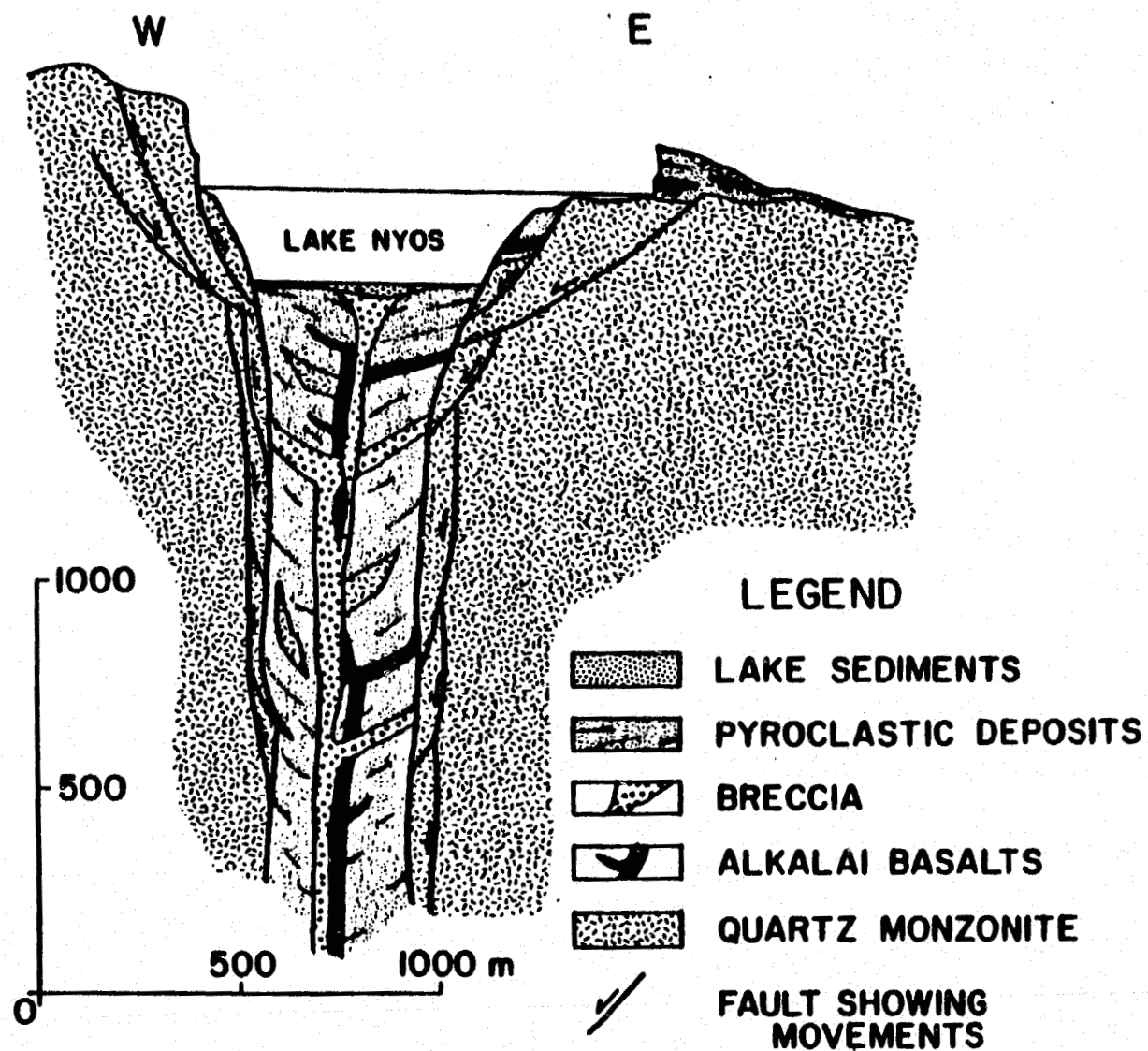


Figure 4. Hypothesized schematic cross section of the diatreme beneath Lake Nyos. Subsurface structure modified from Hearn (1968).

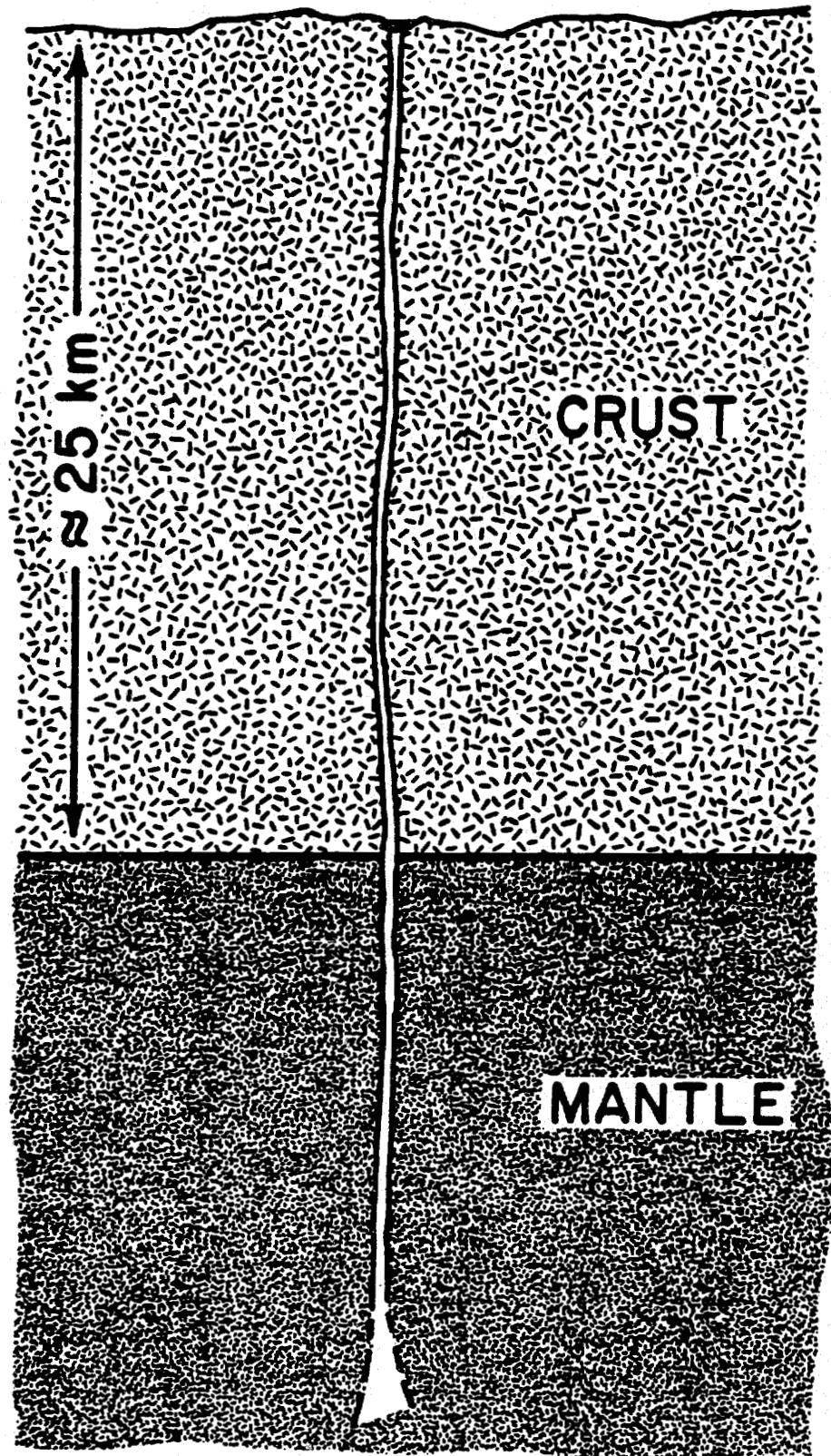


Figure 5. Schematic cross section of Lake Nyos feeder dike at depth. Thickness of dike greatly exaggerated. Actual mantle melting source much deeper than indicated.

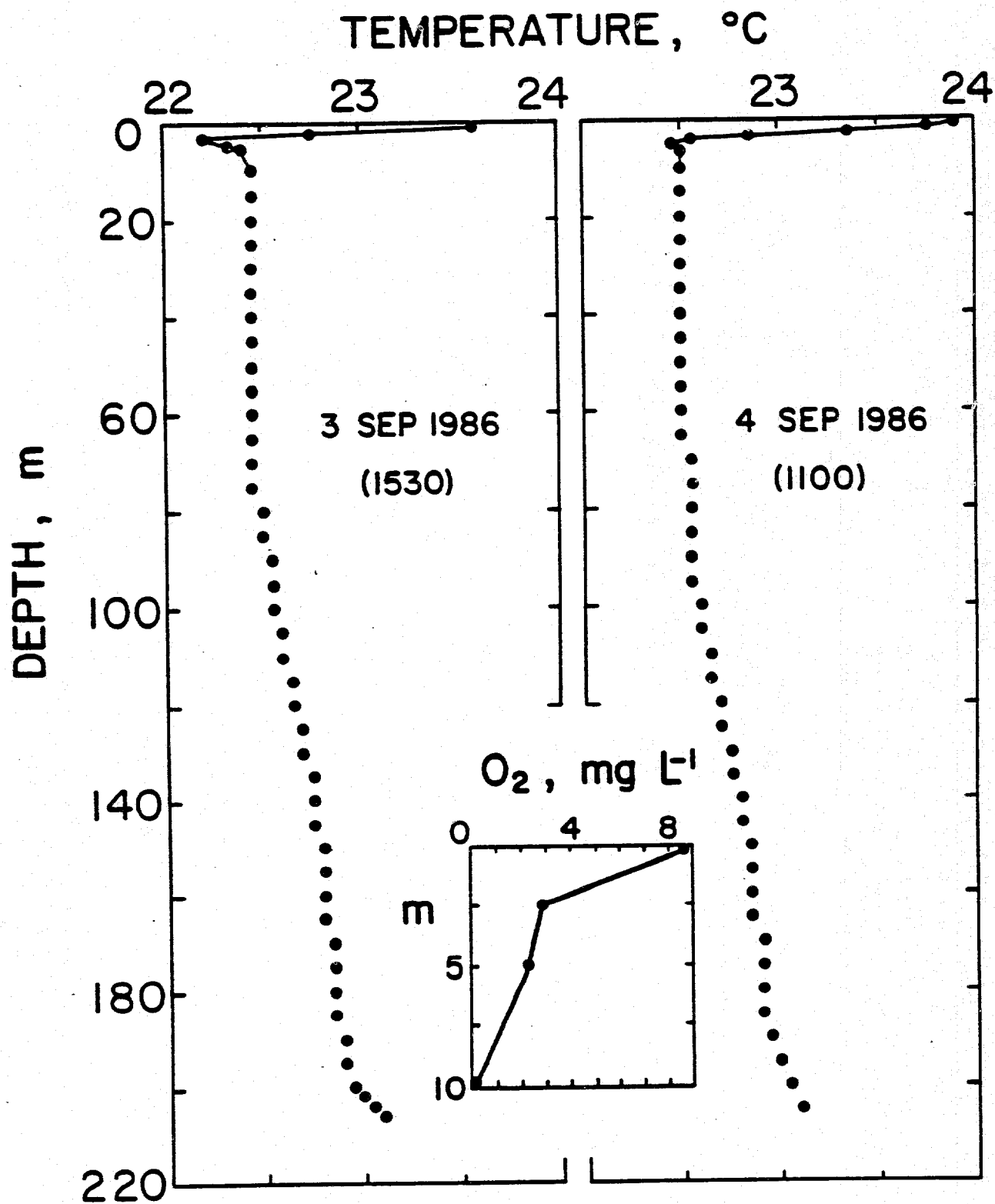


Figure 6. Plots of temperature and dissolved oxygen content versus depth for Lake Nyos. 3 September profile taken from station B; 4 September profile taken from station C.

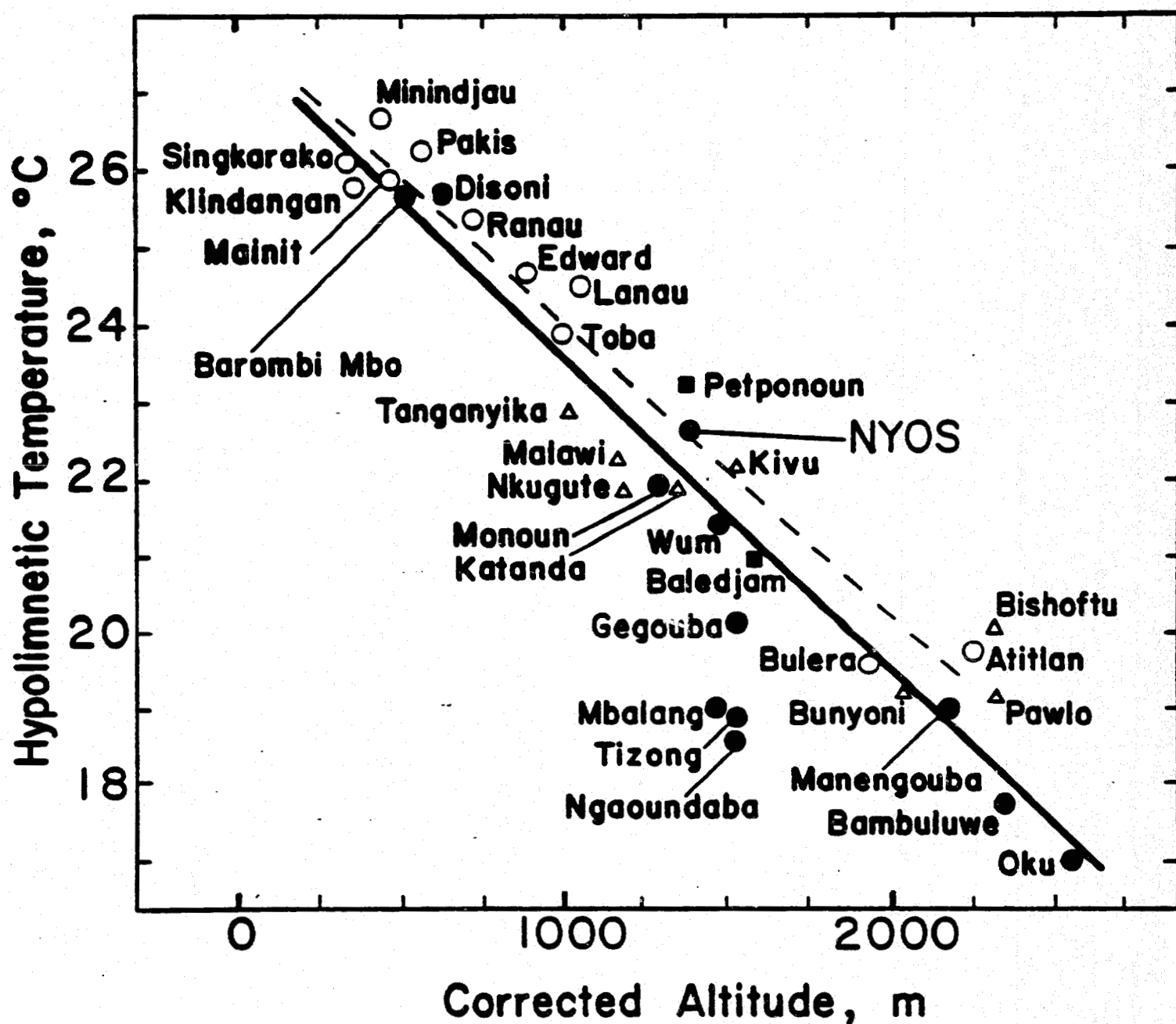


Figure 7. Relationship of bottom water temperature and altitude corrected for latitude in tropical lakes. Solid circles and solid squares are Cameroon lakes (G. Kling, unpubl.). Dashed line and open circles are from Lewis (1973). Open triangles are from Talling (1969), Wood and others (1976), Melack (1978), and Beadle (1981).

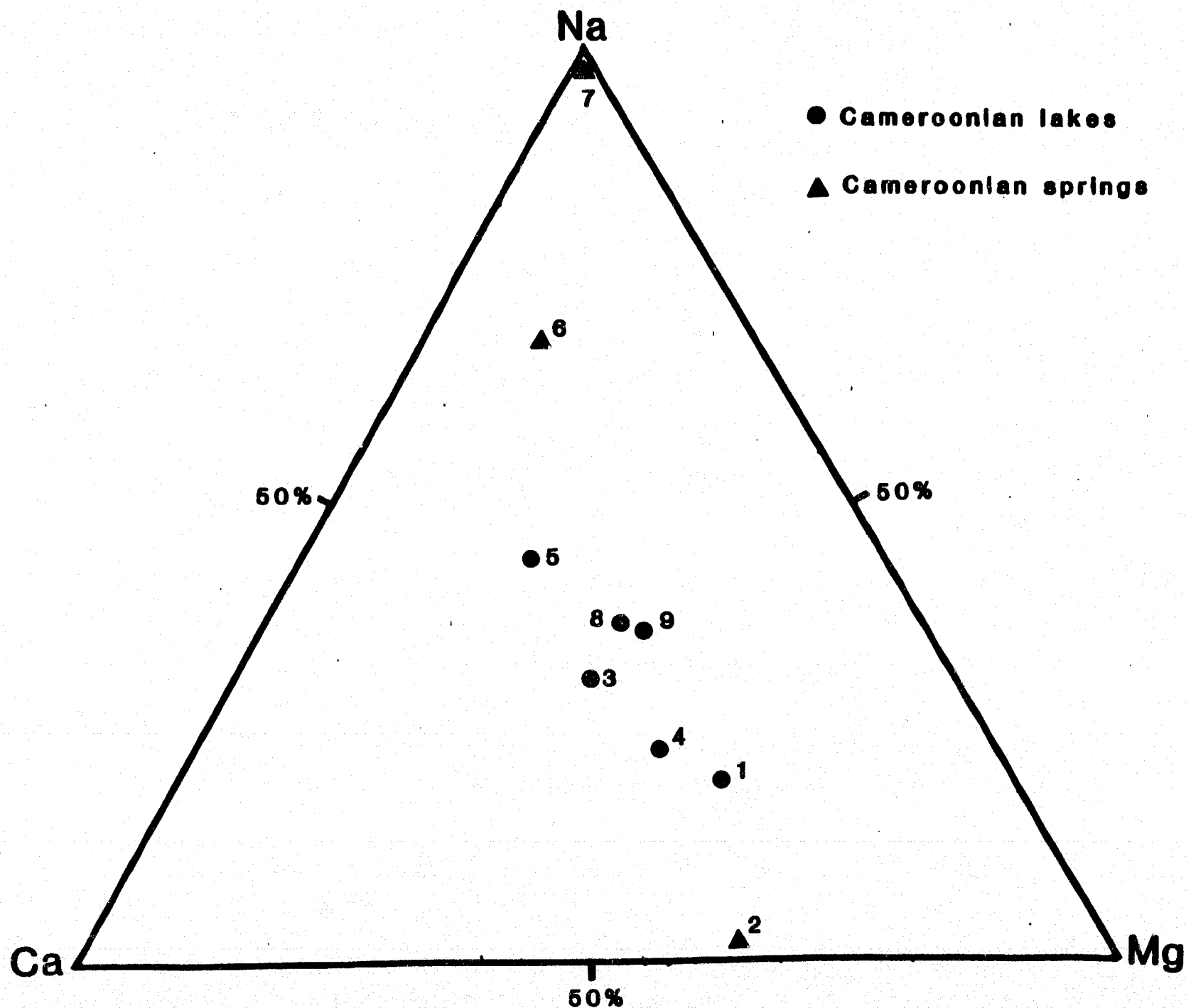


Figure 8. Major cation composition (mole fraction) of Lake Nyos and surrounding springs and lakes: 1= Lake Nyos; 2 = Nyos spring; 3 = Lake Nyl; 4 = Lake Mum; 5 = Lake Bambuluwe; 6 = Luh spring; 7 = Gesel spring; 8 = Lake Monoun; 9 = Lake Barombi Mbo.

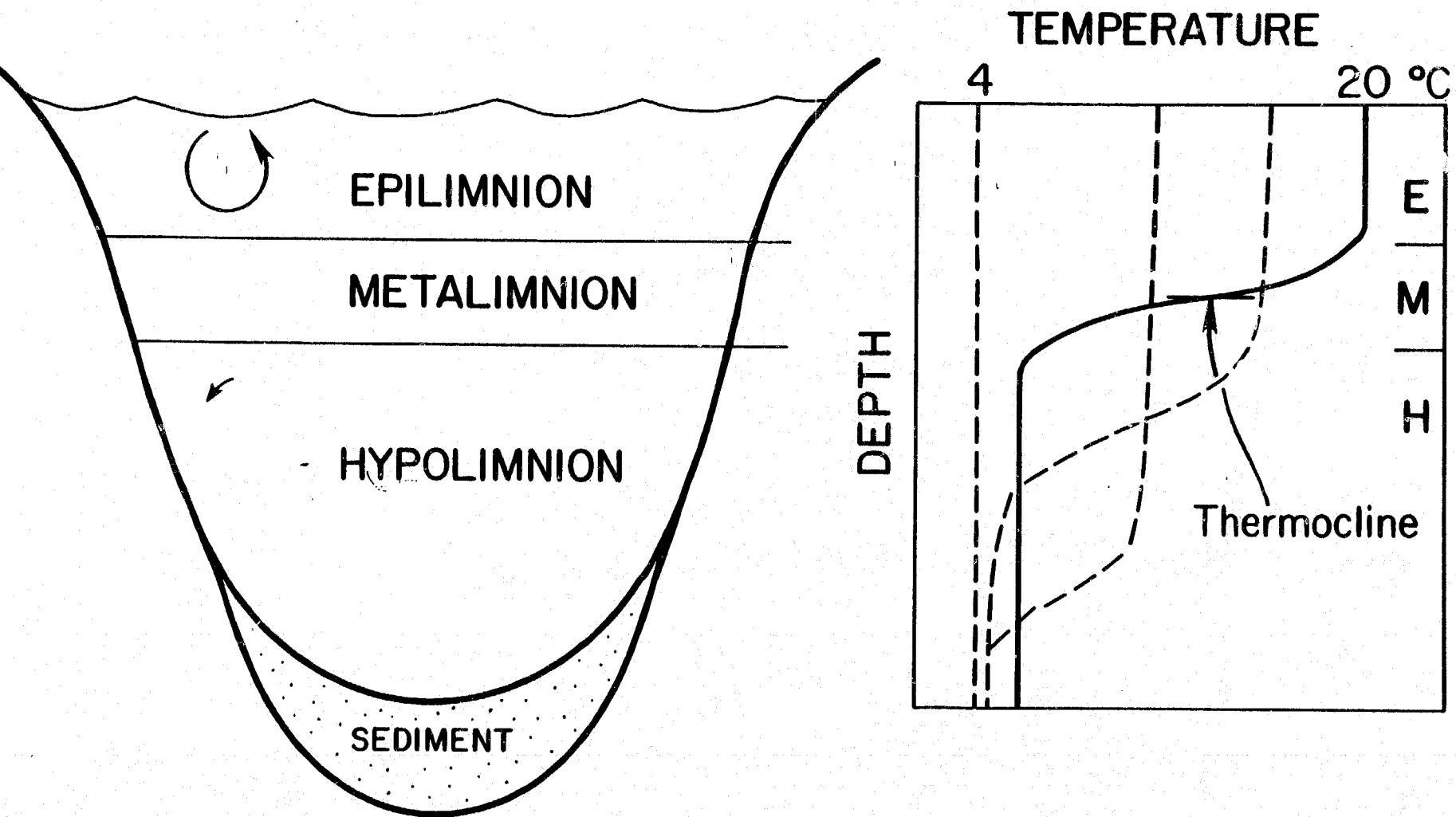


Figure 9. Idealized stratification in a hypothetical lake showing water layers and corresponding temperature relationships. Greater density (temperature) differences across the thermocline increase the stability of stratification.

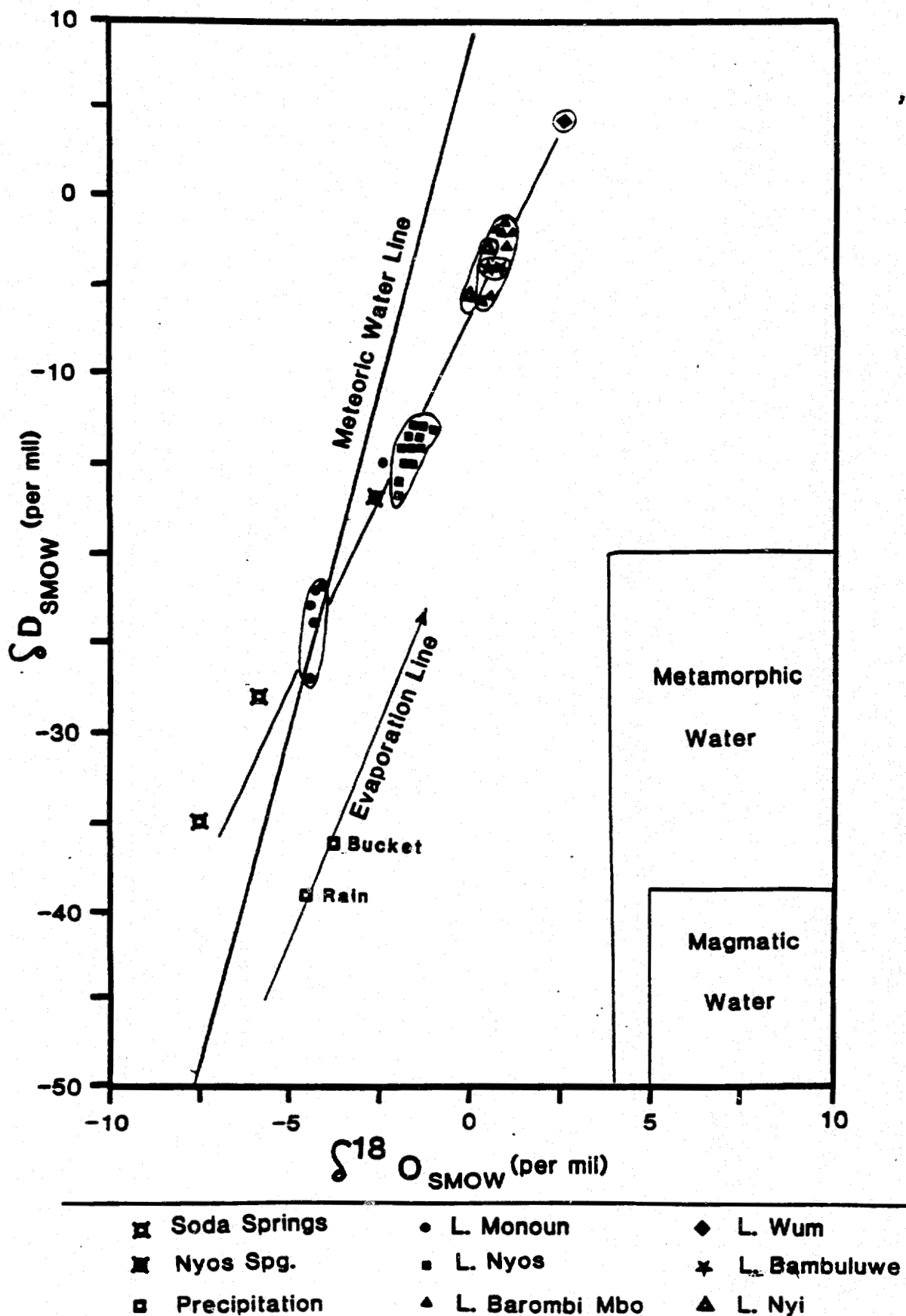


Figure 10. Plot of δD versus $\delta^{18}O$ for precipitation, lake water, and spring water in northwestern Cameroon. The precipitation was collected during a rain storm at Lake Nyos. "Bucket" represents a precipitation sample integrated over 14 days beginning 21 August 1986. Also shown are the meteoric water line of Craig (1961) and the calculated fields of primary magmatic and metamorphic waters as illustrated in Taylor (1970).

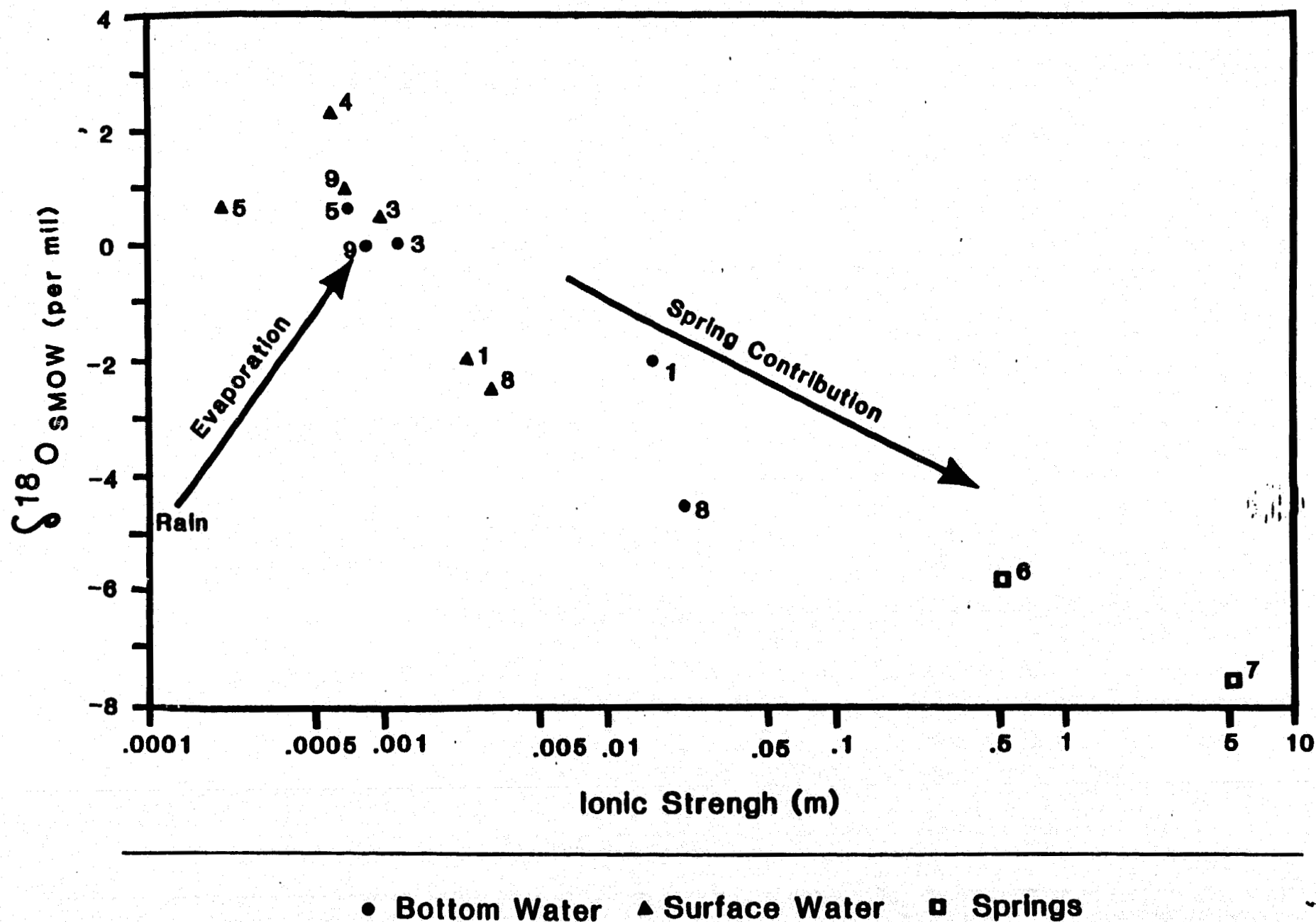


Figure 11-A: Plot of $\delta^{18}\text{O}$ versus ionic strength for Lake Nyos and surrounding lakes and springs (site numbers as in fig. 1). Ionic strengths for Lake Monoun and the springs were calculated from data in Sigurdsson and others (1987) and Marechal (1976) respectively.

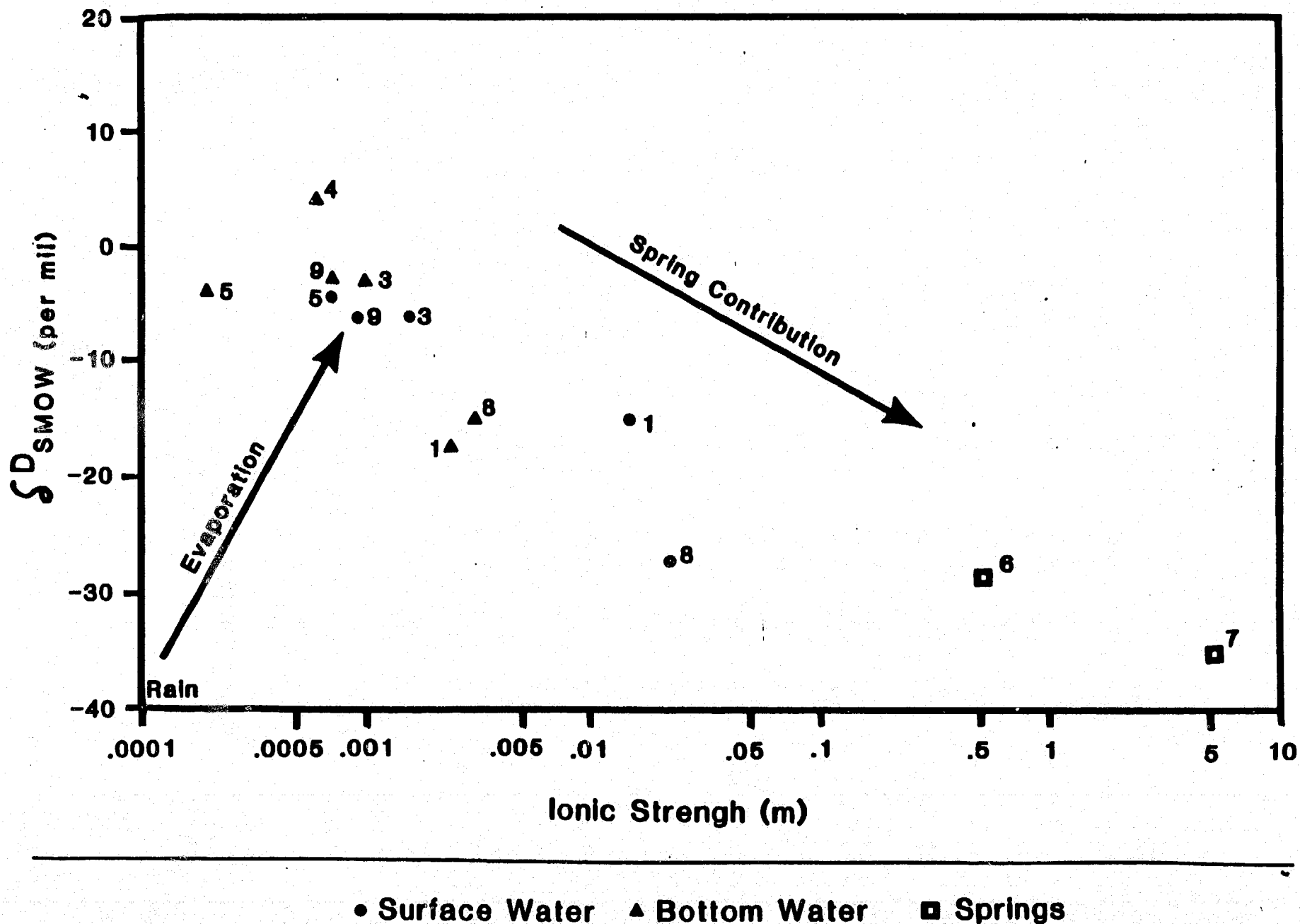


Figure 11-B: Plot of δD versus ionic strength for Lake Nyos and surrounding lakes and springs (site numbers as in fig. 1). Ionic strengths for Lake Monoun and the springs were calculated from data in Sigurdsson and others (1987) and Marechal (1976) respectively.

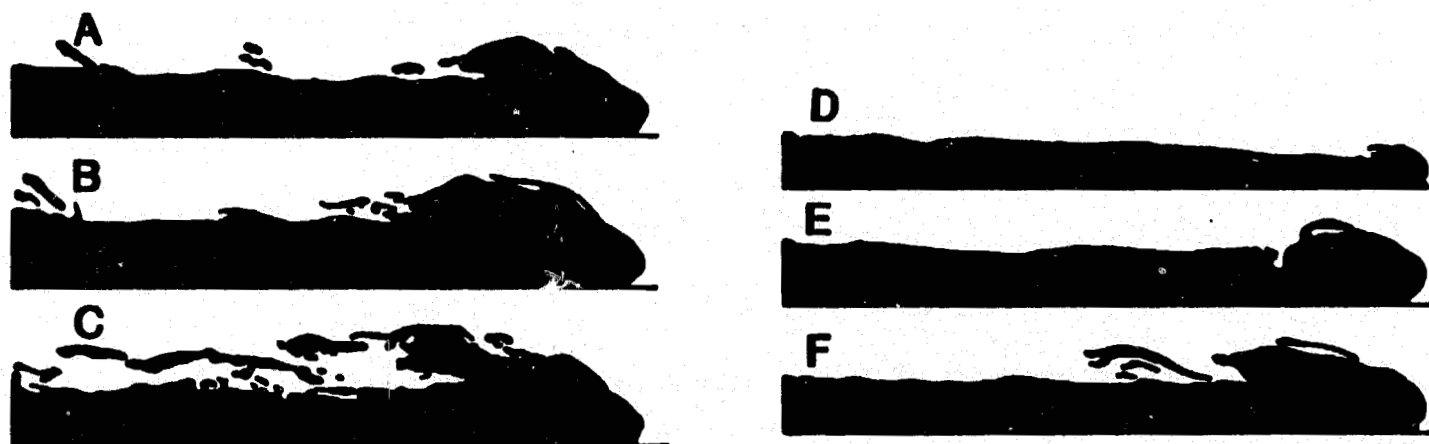


Figure 12. Pictures A-C represent flow of the gas cloud down a steeper slope such as that from Lake Nyos to Nyos village. Pictures D-F represent the more horizontal flow such as from Nyos village to Subum and Mashi (after Simpson, 1982).

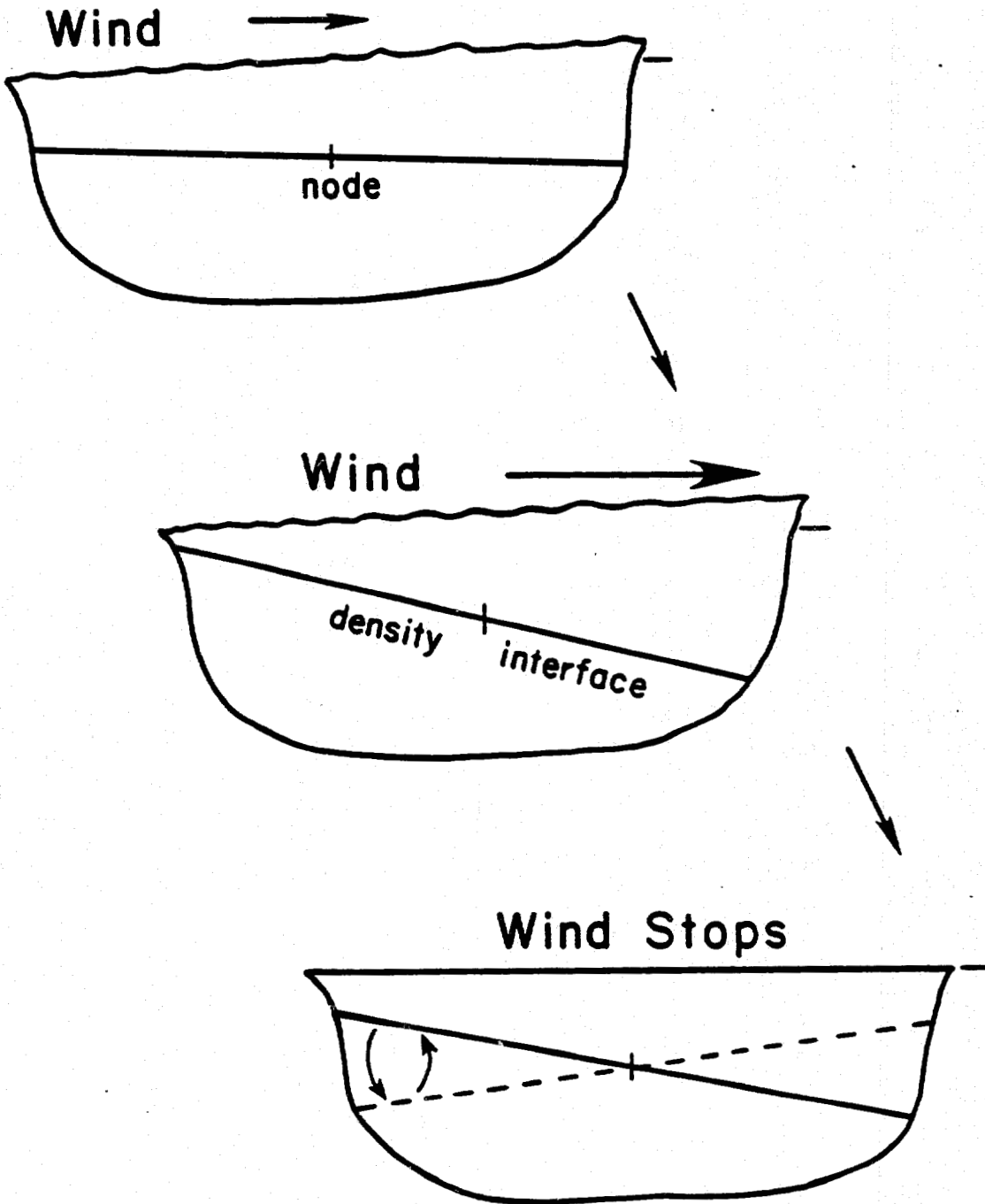


Figure 13. Representation of a uninodal internal wave in a hypothetical lake. Wind or pressure gradients move water to one end of the basin, and the increased water mass depresses the underlying density interface. Deflection of the interface is toward the surface at the opposite end of the basin. When the wind stops, the interface begins to oscillate about the node.

APPENDIX I

Methods

Electron Microprobe Analyses

Analyses of minerals and tephra glasses were obtained by the use of A Cameca Camebax electron microprobe (use of trademarks throughout this report is for identification only and does not constitute an endorsement by the U.S. Government). Widely recognized problems associated with microprobe analysis of glass samples (e.g., alkali migration) were overcome by the use of methods outlined by Devine and Sigurdsson (1983). For major-element analyses of glass, operating conditions were as follows: 15-kV accelerating voltage; 5-nA beam current; 10- μ m beam diameter; and 10-sec count time. For trace-element analyses of glass, operating conditions were: 15-kV accelerating voltage; 100-nA beam current; 10- μ m beam diameter; and 20-sec count time. Mineral analyses were obtained by use of the following conditions: 15-kV accelerating voltage; 15-nA beam current; 2/ μ m beam diameter; and 10-sec count time.

X-ray Diffraction

X-ray diffraction spectrographs were obtained of Lake Nyos bottom sediments. The sediment was first treated with hydrogen peroxide in order to remove as much organic matter as possible, then dried and mounted on a glass slide by sprinkling the sediment onto a smear of epoxy.

Limnological Analyses

Thermal profiles were taken at 1530 on 3 September and at 1100 on 4 September from stations B and C, respectively (Fig. 6). Water temperature was measured with a YSI model 46 analog telethermometer (precision of 0.05⁰C) and thermistor probe. Electrical resistance of the 300-m cable measured less than 1 percent of the thermistor response. The telethermometer

and thermistor were calibrated against a National Bureau of Standards certified thermometer in the boat before use.

Terminal settling velocities (V_g) for sediment particles of radius r were estimated by the use of Stoke's law, $V_g = g(p-p_0)(r^2)/18v$, where g is the acceleration due to gravity, p and p_0 are the densities of the particle and the fluid medium, respectively, and v is the kinematic viscosity. Calculated velocities compare well with velocities measured in reservoirs (Chow, 1964).

CO_2 fugacity was determined by the use of a simple fugacity-pressure relationship, $\ln(f/P) = B_t P/RT$, where f is the fugacity at pressure P and absolute temperature T , R is the universal gas constant, and $B_t = -0.1233 \text{ l mol}^{-1}$ at $295^\circ K$ (Weiss, 1974). CO_2 concentrations were then calculated as $[CO_2] = K_0 \exp[(1-P)v^*/RT]$, where K_0 is derived from the integrated van't Hoff equation, and V^* is the partial molar volume of CO_2 (Weiss, 1974).

Water Sampling

Water samples were collected from Lakes Nyos, Nyi, Wum, Bambuluwe, and Barombi Mbo with a Van Dorn sampler. Isotope samples were placed immediately in glass bottles excluding all headspace.

Samples for cation chemistry were filtered with $0.1\mu m$ membrane filters and acidified with HCl within 24 hours. Samples for anion chemistry were filtered similarly but not acidified. Alkalinity, cyanide, and pH measurements were made within 24 hours after sampling. One surface-sediment sample was collected in Lake Nyos. A fine ferric hydroxide precipitated from some samples upon exposure to air.

Water Chemistry

Water for oxygen analysis was fixed immediately with Winkler reagents when brought to the surface. Samples were titrated with

phenylarsine oxide within 6 hours of collection. The detection limit of this method is $0.05 \text{ mg O}_2 \text{ L}^{-1}$.

The cations were analyzed by the use of induction-coupled, argon-plasma spectroscopy. Chloride and sulfate were analyzed by the use of ion chromatography. Bicarbonate was analyzed by potentiometric titration in the field. Cyanide was measured by specific-ion electrode in the field. Anion-cation imbalances are largely due to loss of iron from solution. Reported values are analytical concentrations. The sediment sample was analyzed for forms of sulfur using a separation technique described in Tuttle and others, (1986).

Isotopes ;

$\delta^{18}\text{O}$ was determined by use of the water- CO_2 -equilibration technique at 25°C ; measurements were made on a Finnigan MAT 251 mass spectrometer. δD was determined by use of the uranium-reduction technique at 850°C ; measurements were made on a modified Nuclide 3-inch, 60° -sector mass spectrometer. All isotope values are reported relative to SMOW.

Gas Methods

Bubbles of gas discharged from both of the sampled soda springs. This gas was trapped in an inverted funnel held under the water surface and then collected in pre-evacuated pyrex bulbs having ground-glass stopcocks. Copious quantities of gas exsolved from deep-water samples of Lake Nyos as the sampler was raised to the surface. Some of this gas leaked-out around the top seal of the sampler. Before the sampler was taken out of the water, it was held a few centimeters below the lake surface, and the gas bubbles were collected as described for the soda springs.

After a storage time of about 3-4 weeks, aliquots of gas were removed from the pyrex bulbs and analyzed for bulk composition by gas chromatography. Additional aliquots were transferred to Corning 1720 glass tubes for subsequent helium isotope analyses. The CO_2 remaining in the pyrex bulbs was

purified cryogenically, and all of the remaining CH_4 was collected on silica gel. The ^{14}C - CO_2 activity was measured on the purified CO_2 . $\delta^{13}\text{C}$ - CO_2 and, following combustion, $\delta^{13}\text{C}$ - CH_4 , were then determined by mass spectrometry.

Modeling

The computer program PHREEQE (Parkhurst and others, 1980) was used to calculate the solution speciation and saturation states of the aqueous phase with respect to various minerals. The program can also simulate types of reactions including addition of reactants to a solution. We used the program to calculate the state of the solution when saturated to varying degrees with CO_2 .

Pathology

Blood samples collected at autopsy were preserved by refrigeration and transported in a frozen state. They were analyzed for ethanol and carboxyhemoglobin (indicative of the presence of carbon monoxide). In addition, cyanide and sulfhemoglobin levels (to monitor for the presence of hydrogen sulfide) were determined. Methemoglobin determinations, which monitor for strongly oxidizing environments, were also carried out. All analyses were done by the use of standard hospital laboratory methods and instrumentation. Tissue samples for microscopic examination were preserved and transported in formaldehyde solution, and slides were prepared by the use of standard histopathology laboratory procedures.

APPENDIX II

Proposed Remediation of Lake Nyos Gas Problem

In order to prevent future occurrences, high levels of dissolved CO_2 in the lake should be reduced. To accomplish this, the bottom waters must be gradually lifted to the surface by the least expensive and most reliable means possible. Water brought to the surface in a controlled manner will release dissolved CO_2 safely.

The most practical solution would be the construction of a system to pipe water from the bottom to the surface. The CO_2 expansion resulting from upward movement of water will generate considerable lifting force and no inputs of energy will be required except for start-up and periodic maintenance. A shutoff valve at the pipe bottom could be used to control the rate of CO_2 discharge. This release technique should not produce harmful concentrations of CO_2 in the nearby area.

Given a volume of $1.7 \times 10^8 \text{m}^3$ in Lake Nyos, it would take five 24-inch-diameter pipes less than three years to completely "treat" a lake volume, assuming no new input. This process must proceed under limnological monitoring in order to keep gas discharge ahead of recharge and to prevent dense waste water from reducing lake stability.

This system could also be positioned at the outlet to allow for safe water withdrawal from the lake, thus lowering the lake surface and permitting dry removal of the weak lava dam (Cobiella, per conversation, 1986).

APPENDIX III
Additional Gas Analyses

Table III-1. Gas concentrations¹ for Lake Nyos corrected for air contamination.

[<=below detection limit]

GAS	Depth		
	201m	155m	103m
(concentration units volume percent)			
Carbon dioxide	98+%	99+%	99+%
Helium	0	0	0
Oxygen	0	0	0
Nitrogen	0	0	0
Argon	0	0	0
Hydrogen	0.22%	<0.02%	<0.02%
Carbon monoxide	<0.0003%	<0.0006%	<0.0006%
Methane	0.30%	0.26%	0.25%
(concentration units ppm by volume)			
Ethane	<0.3	<0.4	<0.4
Ethylene	<0.3	<0.4	<0.4
Propane	<0.3	<0.4	<0.4
i-Butane	<0.3	<0.4	<0.4
n-Butane	1.5	0.4	2.4

¹The components of the gas were quantitated using packed column (Molecular Sieve 5A) G.C. with thermal conductivity detection. The trace hydrocarbon levels were determined by packed column (Porapak Q) G.C. with flame ionization detection.

Table III-2. Results of inorganic acid analysis of ambient air sample¹ at Lake Nyos. Concentrations are reported in total mg. ND means not detected.

Acid	Concentration	Detection Limit
Hydrochloric Acid	ND	0.005
Hydrobromic Acid	ND	0.01
Nitric Acid	ND	0.01
Phosphoric Acid	ND	0.02
Sulfuric Acid	0.03	0.01

¹Tables III-2 and III-3 show the results of pumped ambient air sample (360 L) collected onto silica-gel and carbon matrices. The sample station were located in a small depression adjacent to the spillway at Lake Nyos. The carbon tube was analyzed for volatile organics according to NIOSH method P&CAM 127. The silica-gel tube was analyzed for inorganic acids by NIOSH method P&CAM 339.

Table III-3. Results of volatile organic solvents analysis of ambient air sample¹ at Lake Nyos. Concentrations are reported in total mg. ND means not detected.

Solvent	Concentration	Detection Limit
Acetone	ND	0.06
Methylene Chloride	ND	0.01
Methyl ethyl ketone	ND	0.01
Chloroform	ND	0.01
Ethylene dichloride	ND	0.01
1,1,1-Trichloroethane	ND	0.01
Benzene	ND	0.009
Carbon tetrachloride	ND	0.03
p-Dioxane	ND	0.01
Trichloroethane	ND	0.01
Perchloroethylene	ND	0.02
Xylenes	ND	0.009
Styrene	ND	0.01
Toluene	ND	0.009

¹Tables III-2 and III-3 show the results of pumped ambient air samples (360 L) collected onto silica-gel and carbon matrices. The sample station were located in a small depression adjacent to the spillway at Lake Nyos. The carbon tube was analyzed for volatile organics according to NIOSH method P&CAM 127. The silica-gel tube was analyzed for inorganic acids by NIOSH method P&CAM 339.

Table III-4. Lake Nyos area draeger-tube analysis of ambient air at the spillway of Lake Nyos.

Compound ¹	Detection Limit (ppm)
Hydrogen Sulfide (H ₂ S)	0.3
Carbon Monoxide (CO)	2.0
Sulfur Dioxide (SO ₂)	100
Methane (CH ₄)	5000
Hydrocyanic Acid (HCN)	0.5

¹None of these compounds were detected in ambient air at the spillway of Lake Nyos.

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